7-2015

CARBON STORAGE POTENTIAL OF WINDBREAKS ON AGRICULTURAL LANDS OF THE CONTINENTAL UNITED STATES

William Ballesteros Possu
William University of Nebraska-Lincoln, wballesterosp@gmail.com

CARBON STORAGE POTENTIAL OF WINDBREAKS ON AGRICULTURAL LANDS OF THE CONTINENTAL UNITED STATES

by

William Ballesteros Possu

A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Natural Resources Sciences

Under the Supervision of Professor James R. Brandle

Lincoln, Nebraska

June, 2015

CARBON STORAGE POTENTIAL OF WINDBREAKS ON
AGRICULTURAL LANDS OF THE CONTINENTAL UNITED STATES

William Ballesteros Possu, Ph.D.

University of Nebraska 2015

Adviser: James R. Brandle

Agricultural production systems face major challenges under climate change scenarios in terms of expected negative impacts on productivity. Windbreaks perform several ecosystems functions that improve the local and regional capacity of crop systems to increase yields and mitigate greenhouse gas (GHG) emissions. This is predominantly accomplished by the windbreak trees storing carbon (C) in their above- and belowground woody tissue, while reducing carbon dioxide (CO_2) emissions either through avoidance of emissions or through energy savings. However, available and reliable data for estimating windbreak contributions to whole-farm and regional C assessments are scarce and, in most regions, do not exist.

The main objective of this research was to analyze the C storage potential of field and farmstead windbreaks and to estimate the extent of potential reduction in C emissions due to the presence of windbreaks in different farming scenarios. This study focused on 1) identifying allometric equations suitable for use with the more open-grown trees in windbreaks, 2) analyzing the avoidance of carbon emissions for different crops by planting windbreaks, and 3) evaluating hypothetical farms synthesized with different windbreak designs together with cropping systems and farmstead.

There were several important results from this study. First, the Jenkins model was found to be the best tool for estimating biomass/C storage potential for windbreaks. Second, there were many suitable tree species with promising carbon storage potentials for designing diverse windbreaks. Third, different windbreak designs can offset total carbon emissions from cropping systems in small and large-scale farms. Fourth, windbreaks have an important impact in carbon emissions reduction when planted on agricultural lands. Fifth, two- or three row field windbreaks can potentially offset most carbon crop emissions. Sixth, key aspects determining the windbreak potential for offsetting carbon emissions in farming operations included: site conditions, tree species, house size, windbreak designs, and farmers' willingness to adopt these changes. The findings from this project provide further evidence of the role windbreaks can play in GHG mitigation by agriculture and describe a reasonable, science-based approach for estimating the level of these contributions.

ACKNOWLEDGEMENTS

I want to express my deepest gratitude to Fulbright, Institute of International Education (IIE), Ministry of National Education of Colombia, U.S. Forest Service-National Agroforestry Center (USDA-NAC), University of Nariño, University of Nebraska, and Nebraska Statewide Arboretum for their support, encouragement and thoughtful guidance to study in the United States. Their valuable support and permanent supervision always kept me in the right direction. Being a Fulbright scholar has been an unforgettable learning experience. Without their support I could not have graduated successfully as Doctor of Philosophy at the University of Nebraska. I am thankful to have been a Fulbright Scholar.

Special thanks to my Professor and thesis adviser, Dr. James R. Brandle. His persistent advice and permanent readiness always guided me to solve the main concerns of my research. Working with him has been a priceless learning experience. My special thanks to Dr. Michele Schoeneberger for her support and guidance throughout my dissertation project. Her critical suggestions and comments helped me evolve my initial dissertation proposal. She has made a real difference in shaping my work.

My sincere thanks go to Dr. Charles Francis for his support to face the main challenges of my Doctoral Studies. I would like to thank Drs. Erin Blankenship and David Wedin for their support, comments and suggestions. I am privileged and honored to have them on my dissertation committee.

Finally, I am greatly indebted to my family. Their persistent support and reliance in me empowered me to complete successfully my Ph.D. studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF APPENDIX TABLES

LIST OF FIGURES

INTRODUCTION

As atmospheric CO_2 concentrations rise, the urgency to find effective tools to reduce the rate of increase is essential. In the United States, agricultural systems are dominated by monoculture practices where only one type of crop is grown on a large scale. These large farms are highly reliant on fossil fuel-based inputs to maximize agricultural yields and meet the food demands of a steadily growing world population. The intensity of these practices has led to the U.S. agricultural sector becoming an important source of greenhouse gases (GHG) (USEPA 2014). Agroforestry, the intentional integration of forestry and agriculture within agricultural operations for building more weather and economic resilient farms, ranches and rural communities can serve as one option for reducing the use of off-farm inputs and increasing the carbon storage potential within conventional cropping systems in the United States (Brandle et al. 1988, Nair et al. 2004, Brandle et al. 2009). Evaluating the carbon storage potential for agroforestry systems on farm scenarios is critical if we are to determine the carbon storage potential of these practices on agricultural lands.

Of the five main agroforestry practices used in the United States, crop windbreaks are one of the most commonly applied practices and are especially promising in regards to sequestering C and reducing CO_2 emissions in agriculture. Windbreaks store large amounts of C in their above- and belowground woody tissue while also reducing CO_2 emissions through emission avoidance and energy savings. Along with these C services, windbreaks provide wind protection to the crop and over the long term increase crop yields along with providing soil conservation, wildlife habitat, and other ecosystem services valued by the land owner and society (Kort 1988, Brandle et al. 2009). While research has demonstrated the C benefits of these systems, being able to quantify these contributions will help inform decision makers, at the land management scale on up to those developing policies and programs, on the value of windbreaks as a viable management activity in support of developing environmentally and economically friendly agriculture. The main objective of this research was to analyze the carbon storage potential of field and farmstead windbreaks, the two types most commonly used in the United States, and to estimate the extent of potential reduction in emissions due to the presence of windbreaks in different farming scenarios in the continental United States.

This project is an exploratory study regarding how one can easily yet accurately assess the C sequestrating potential of windbreak trees and serve as a C-offsetting mechanism on agricultural systems, and what these numbers tell us regarding the potential of windbreaks as an agricultural GHG mitigation activity. Chapter 1 describes the effect of predicted climate change on agriculture and the impact of conservation practices and agroforestry on the C balance on cultivated lands. Chapter 2 is an overview of state-of-the-art of agricultural systems and agroforestry systems, especially field and farmstead windbreaks, for reducing C emissions and storing C on-farm under various farming scenarios. Chapter 3 examines the suitability of existing forest derived biomass equations for estimating C in windbreak trees, and, from that information, then developing a protocol to estimate C storage potential for several hardwood and conifer tree species suitable for windbreaks in different regions of the United States. Chapter 4 evaluates the C storage potential of different windbreak designs. Chapter 5 analyzes the reduction of emissions for windbreak designs on farm operations. Chapter 6 assesses the

C balance for four different case studies with windbreaks, farmsteads and crop systems.

Chapter 7 summarizes the major findings from this study and points out further research.

References

Brandle, J.R., Hintz, D. L. and Sturrock, J.W. 1988. Windbreak Technology, Elsevier Science Publishers, Amsterdam, 598 p.

Brandle, J.R., Hodges, L., Tyndall, J. and Sudmeyer, R.A. 2009. Windbreak practices.. In: Garrett H.E. (ed.) North American Agroforestry, an integrated science and practice, 2nd, American Society of Agronomy, Madison, WI, USA, pp 75-104.

Kort, J. 1988. Benefits of windbreaks to field and forage crops, Agriculture Ecosystems and Environment 22/23:165-190.

Nair, P.K.R. 2004. Agroforestry: Trees in support of sustainable agriculture. In: Hillel, H., Rosenzweig, C., Powlson, D., Scow, K., Singer, M., Sparks, D. (ed.) Encyclopedia of Soils in the Environment, Elsevier, London, UK. pp 35-44.

U.S. Environmental Protection Agency (USEPA) 2014. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012, EPA 430-R-14-003, Washington, D.C., U.S. Environmental Protection Agency, http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf. (7/1/2015).

CHAPTER 1: BACKGROUND

Climate change, a set of natural and anthropogenic processes, has become an important issue to society. Despite scientific evidence started by Arrhenius in 1896 (Arrhenius 1896), global warming was a theory not widely accepted by the scientific community. In 2013, the Intergovernmental Panel on Climate Change (IPCC 2013) reported new and stronger evidence confirming that it was extremely likely that most of the warming observed over the last 50 years was one of the consequences of radiative forcing caused by anthropogenic greenhouse gas (GHG) emissions. Energy supply, industry, land use, land-use change, transportation, and agriculture have been listed as the major GHG contributors (IPCC 2007). Current farming practices, land clearing, input production and use, and decomposition of organic residues make conventional agriculture a significant contributor of GHG (IPCC 2007). These agricultural GHG emissions increase as materials move from the farm-gate to consumers. Agricultural goods are transported, packed, refrigerated, and processed before reaching the grocery shelves adding additional emissions. One of the largest contributors to GHGs is household transportation to and from supermarkets.

Climate changes have led to large-scale environmental threats for humans and ecosystems. From North to South, ecosystems are being transformed on such an extraordinary scale and an exceptional pace (Ryan et al. 2008) that humanity needs sustained actions to deal with the steady increase of GHGs (Adams et al. 2008).

Worldwide governmental and non-governmental agencies are developing adaptive actions and mitigation tools to cope with the global warming effects. These efforts include improvements in the efficiency of fossil-fuel-fired power plants, adoption of alternative energy technologies (Sims et al. 2003, USEPA 2012), aquifer and deep-sea storage of CO_2, mineral carbonation (Vogt et al. 1996, O'Connor et al. 2000), biological uptake and storage in woody plant materials (Dixon et al. 1994, IPCC 2000, Nair et al. 2009a, Palm et al. 2005). Many of the above are being applied at local-scales. Other potential options are still under discussion or in nascent stages of development; thus many questions still remain before these tools can be applied as a global solution.

Global initiatives to assess the world's GHG emissions and forest C storage have been launched. Reducing emissions from deforestation and forest degradation and adaptation are proposed in a number of venues: 1) the United Nations framework convention on climate change (UNFCCC); 2) the convention on biological diversity (CBD) (Munroe and Mant 2014); 3) the land-change evaluation, reporting and tracking system (ALERTS) (PSI 2015); and 4) national gas emission inventory (IPCC 2006). In April, 2015 USDA rolled out the 'Building Blocks for Climate Smart Agriculture and Forestry', a comprehensive approach for farmers, ranchers and forest managers to begin addressing the issues that will be facing them under climate change. Chief among these efforts will be GHG mitigation actions, including both those that sequester C and those that reduce or avoid GHG emissions.

Among the tools to sequester C, biological uptake and storage in woody plant materials are usually recognized as a feasible way to mitigate GHG emissions (McPherson 2007). Improved forest management practices aimed to mitigate and adapt to climate change have an enormous potential to enhance C stocks. These practices, reforestation, afforestation, and agroforestry systems (AFS) play an important role in the scenarios of C capture and storage (Brandle et al. 1992, Dixon et al. 1994, IPCC 2000, Albrecht and Serigne 2003, Brandle et al. 2004, Palm et al. 2005, IPCC 2007, Nair et al 2009b, Nair et al. 2010, Udawatta and Jose 2011), including contributing to the reduction of forest loss and degradation (Steenwerth et al. 2014). However, although the rate of forest loss has slowed, deforestation, mainly conversion of forest into agricultural land, is continuing at an alarmingly high rate (FAO 2014).

Expansion of agriculture, along with human population growth and the rising demand for goods and services, places enormous pressure on forest ecosystems, limiting the development of new forest land. Agroforestry, as one of the several climate-change adaptation and mitigation tools that can be established on cultivated lands, serves to help farmers and ranchers to deal with the uncertainties of climate-change through its tree or forest-derived functions (Schoeneberger et al. 2012). These functions range from modified microclimate that can improve production and reduce energy usage to creating critical diversity in agricultural landscapes for supporting wildlife habitat.

The woody components in AF are also an important C sink due to the amounts and duration of the C stored in the woody biomass, to the fast growing rate of some trees, and to their low management costs (Nair 2004, Udawatta and Jose 2011). By including trees on agricultural lands in support of agriculture, these lands can effectively increase the amount of C stored by agricultural systems, thereby offsetting more of their emissions (Kursten 2000). While evidence supports this role, wide-ranging data on agroforestry practices in the United States are not available for accurate and easy estimation of their current and future contributions to direct and indirect C sequestration on croplands (Nair et al. 2010, Udawatta and Jose 2011, Eagle et al. 2011, Schoeneberger et al. 2012).

Of the common agroforestry practices used in the United States, windbreaks (also referred to as shelterbelts) hold special promise as a tool to help support farm and ranching operations, including increased C sequestration and GHG mitigation. Field windbreaks, in particular, reduce wind speed, protect soil and crops, and control snow, all while storing C and reducing GHG emissions. Updated, standardized and representative statistics on C storage and emissions reductions are not yet readily available for this agroforestry practice, especially across the many regions in which they can be planted (Udawatta and Jose 2011, Schoeneberger et al. 2012, Nair 2012).

Although the limited literature indicates net gains in C sequestration by windbreaks (Udawatta and Jose 2011), lack of rigorous data on the area under this practice (Dixon 1995, Nair 2012, Schoeneberger et al. 2012), and inconsistent experimental procedures and data-gathering protocols (Udawatta and Jose 2011, Nair 2012) make these data very difficult to compare and generalize. Several methodological challenges face researchers interested in making comparisons among these estimates. This exploratory study was focused on three main goals: 1) comparing suitability of different allometric equations for estimating the more open-grown tree growth in windbreaks, 2) evaluating the potential levels of indirect carbon benefits that can be conferred by field and farmstead windbreaks in different farming scenarios across regions reduction and 3) evaluating windbreak scenarios for their capacity to reduce C emissions and store C on farms by windbreaks.

References

Adams, H.D., Guardiola-Claramonte, M., Barron-Gafford, G.A., Villegas, J.C., Breshearsa, D.D., Zou C.B., Trocha, P.A. and Huxmana, T.E. 2008. Temperature sensitivity of drought-induced tree mortality: Implications for regional die-off under global change-type drought, proceeding of the National Academy of Sciences 106 p.

Arrhenius, S. 1896. Influence of carbonic acid in the air upon the temperature of the ground, Philosophical Magazine 41:237-276.

Brandle J.R., Hodges, L. and Zhou, X. 2004. Windbreaks in North American agricultural systems, Agroforestry Systems 61:65-78.

Brandle, J.R., Wardle, T.D. and Bratton, G.F. 1992. Opportunities to increase tree plantings in shelterbelts and their potential impacts on carbon storage and conservation, Forests and Global Change, Edited by R.N. Sampson and D. Hair. American Forests, Washington, D.C. pp 157-175.

Dixon, R. K., Brown, S., Houghton, R.A., Solomon, A. M., Trexler, M.C. and Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystems, Science 263:185-190.

Eagle, A.J., Henry, L.R., Olander, L.P., Haugen-Kozyra, K., Millar, N. and Philip, G. R. 2011. Greenhouse gas mitigation potential of agricultural land management in the United States: A Synthesis of the Literature, Second edition, Duke University. 68 p.

FAO, (Food and Agriculture Organization of the United Nations) 2014. State of the word’s forest: Enhancing the socioeconomic benefits from forest. http://www.fao.org/forestry/sofo/en/ (7/1/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2000. Land use, land ‘use change, and forestry: special report. Intergovernmental Panel on Climate Change, on line at: http://www.ipcc.ch/pdf/special-reports/spm/srl-en.pdf (7/1/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2006. IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/ (7/1/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2007. Climate change mitigation. Contribution of Working Group III to the Fourth Assessment Report of the intergovernmental Panel on Climate Change, Cambridge, United Kingdom: Cambridge University Press, New York, USA, pp 862.

IPCC, (Intergovernmental Panel on Climate Change) 2013. The physical science basis. Working group I contribution to the IPCC fifth assessment report. http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_TechnicalSummary.pdf (7/1/2015).

Kürsten, E. 2000. Fuel wood production in agroforestry systems for sustainable land use and CO2 mitigation, Ecological Engineering, 16:S69-S72.

McPherson, E.G. 2007. Urban tree planting and greenhouse gas reduction. http://www.fs.fed.us/psw/programs/uesd/uep/products/psw_cufr684_TreesAndGHG.pdf (7/1/2015).

Munroe, R. and Mant, R. 2014. REDD+ and adaptation: identifying complementary responses to climate change. UN-REDD Program, Info Brief. http://www.unredd.net/index.php?option=com_docman&task=doc_download&gid=13871&Itemid=53 (7/1/2015).

Nair, P.K.R. 2004. Agroforestry: Trees in support of sustainable agriculture. In: Hillel, H., Rosenzweig, C., Powlson, D., Scow, K., Singer, M., Sparks, D. (eds.), Encyclopedia of Soils in the Environment, Elsevier, London, UK, pp 35-44.

Nair, P.K.R. 2012. Carbon sequestration studies in agroforestry systems: a reality-check, Agroforestry Syst 86:243-253.

Nair, P.K.R., Kumar, B.M. and Nair, V.D. 2009a. Agroforestry as a strategy for carbon sequestration, J. Plant. Nut. Soil Sci 172:10-23.

Nair, P.K.R., Nair, V.D., Kumar, B. M. and Haile, S.G. 2009b. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal, Environmental Science and Policy 12(8):1099- 1111.

Nair, P.K.R., Nair, V.D., Kumar, B. M. and Showalter, J.M. 2010. Carbon Sequestration in Agroforestry Systems, In: Advances in Agronomy,. Donald, L.S (ed.). Academic Press 108:237-307.

O'Connor, W.K., Dahlin, D.C., Nilsen, D.N., Walters, R.P. and Turner, P.C. 2000. Carbon dioxide sequestration by direct mineral carbonation with carbonic acid, Albany Research Center, Office of Fossil Energy, US Department of Energy, DOE/ARC. http://www.osti.gov/bridge/servlets/purl/896218-YSyk5m/896218.pdf (7/1/2015).

Palm, C.A., van Noordwijk, M., Woomer, P.L., Alegre, et al. 2005. Carbon losses and sequestration with land use change in the humid tropics. In: Slash and burn agriculture, the search for alternatives, Palm, A.., Vosti, S.A., Sanchez, P.A. and. Ericksen, J.P. (eds.). Columbia University Press, New York, USA, pp 42-63.

PSI, (Planetary Skin Institute). 2015. Automated Land-change Evaluation, Reporting, and Tracking System (ALERTS). http://www.planetaryskin.org/rd-programs/resource-nexus/global-land-change-detection (7/1/2015).

Ryan, M.G., Archer, Birdsey, S.R., Dahm, C.N., et al. 2008. Land Resources. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, A Report by the U.S. Climate Change Science

Program and the Subcommittee on Global Change Research, Washington, DC, USA, 362 pp.

Sims, H.E.R., Hans-Holger, R. and Ken, G. 2003. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation, Energy Policy 31:1315–132.

Steenwerth, K.L., Hodson, A.K., Bloom, A.J., Carter, M.R., Cattaneo, A., Chartres, C.J. and Jackson, L.E. 2014. Climate-smart agriculture global research agenda: scientific basis for action, Agriculture and Food Security 3:11. http://www.biomedcentral.com/content/pdf/2048-7010-3-11.pdf (7/1/2015).

Udawatta, R.P. and Jose, S. 2011. Carbon sequestration potential of agroforestry practices in temperate North America. In: Kumar, B. Mohan; Nair, P.K.R. Carbon sequestration potential of agroforestry systems: opportunities and challenges, Advances in Agroforestry, 1st (ed.) 17:17-42.

U.S. Environmental Protection Agency (USEPA) 2012. Roadmap for incorporating energy efficiency/renewable energy policies and programs into state and tribal implementation plans. http://epa.gov/airquality/eere/pdfs/appendixD.pdf (7/1/2015).

Vogt, K.A., Vogt, D.J., Palmiotto, P.A., Boon, P., O'Hara, J. and Asbjornsen, H. 1996 Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species, Plant Soil 187:159-219

CHAPTER 2: AN OVERVIEW: THE POTENTIAL ROLE OF AGROFORESTRY IN ENHANCING CARBON SEQUESTRATION AND REDUCING GREENHOUSE GAS EMISSIONS ON AGRICULTURAL LANDS

Introduction

Increasing levels of atmospheric greenhouse gases (GHGs) are triggering changes in our climate. In 2013, the Intergovernmental Panel on Climate Change (IPCC 2013) reported new and stronger evidence confirming that most warming observed over the last 50 years was attributable to anthropogenic causes. Climate change may impact society and ecosystems in a broad variety of ways (USEPA 2012, 2014a). There are conflicting perspectives about how to deal with the extent of its negative impacts. Dealing with these impacts requires countries around the world to reduce their atmospheric GHG emissions (IPCC 2014a), which in turn involves an enormous investment of capital and human resources, and a radical transformation of production systems and consumptive behavior (FAO 2010, IPCC 2013).

Decision makers are discussing strategies to reduce GHG emissions. However, some strategies are not well received, and nothing is agreed upon by all nations (Udawatta and Jose 2011). In order to resolve this conflict, the world needs reliable tools to inform decision-makers, international negotiators, and public opinion about climate-change adaptation and mitigation management options.

Although the impact of the natural and anthropogenic perturbations on GHG emissions is permanent, future changes may be substantially reduced to safer levels (FAO

2010, CAST 2011,). Personal lifestyle changes that reduce the use of fossil fuels and reinforce sustainable farming can help minimize our C footprint. The Climate Smart Agriculture Approach (FAO 2010) offers a set of practices to tackle atmospheric GHGs. Sustainable methods for managing GHGs in United States agricultural lands have been summarized in a CAST report (2011) and include: conservation, converting croplands to pasture, no till, reduced fuel use, forestation and reforestation. Agroforestry, the integration of woody plants into crops/livestock operations, is one of these methods.

Since the Kyoto Protocol, agroforestry systems have gained more attention as a strategy to capture and store carbon (C) (IPCC 2000a, Shibu and Sougata 2012). The IPCC (2001) reports that, "Agroforestry can both sequester C and produce a range of economic, environmental, and socioeconomic benefits." Consequently, integrating agroforestry onto the landscape is considered one of the best "no regrets" measures to help communities mitigate, adapt, and become resilient to the impacts of climate change (Rao et al. 2007).

Despite agroforestry systems being recognized as a feasible tool to provide tangible and intangible goods and services while producing C services (Schoeneberger 2009, Nair et al 2010), many gaps need to be filled to increase our understanding on how to best manage agroforestry for these services. These gaps can be addressed by increasing comprehensive scientific knowledge (Nair and Nair 2003), generating accurate and reliable data (Nair and Nair 2003, Schoeneberger 2009, Eagle et al. 2012), unifying methodological approaches (Nair and Nair 2003, Udawatta and Jose 2011), and evaluating their impacts on farming operations and C budgets (Nair and Nair 2003, FAO 2010, CAST 2011).

Climate change presents a planet-wide experiment for researchers. There are many interventions under investigation. Integrating agroforestry practices on cultivated lands to tackle GHG emissions is one of them. Sound agroforestry research is the first step to understanding the factors related to climate change and how they will enhance the carbon storage potential for agricultural systems.

Carbon Cycle

The C cycle is the flux of C among the atmospheric, oceanic, terrestrial biosphere and geological deposits (Falkowsky et al. 2000, IPCC 2014b) which is stored in "carbon pools" (C stocks or reservoirs) (Sabine et al. 2004, IPCC 2007a, Schuur et al 2008). Within these pools, C flows from one source to another, transforming C from source to sink, and vice versa (Houghton 2007). According to the United Nations Framework Convention on Climate Change, "A [C] source is any process or activity that releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas into the atmosphere; whereas a sink is any process, activity, or mechanism which removes C from the atmosphere" (Articles 1.8 and 1.9, IPCC 2000a). Therefore, C sequestration is the capture and storage of C that would otherwise be emitted into the atmosphere (IPCC 2000b, FAO 2008).

Concentrations of carbon dioxide (CO_2), a major cause of global warming, have increased at their fastest rate for the last 30 years (NOAA 2015). The rise in CO_2 availability directly impacts photosynthetic processes evoking a wide range of physiological and morphological responses in plants (Dukes 2000, Field et al. 2008). It is believed that most woody plants can produced more biomass at an elevated CO_2

concentration (Polle et al. 2001, Usami et al. 2001, Stiling et al. 2004, Ainsworth and Long 2005, Norby et al. 2005, Huang et al. 2007, Wang 2007), however, many uncertainties remain about which tree species will benefit or be constrained at that concentration because the benefits of "growth" may be more appealing to pest or diseases (Lindroth et al. 1993, Scheffer et al. 2006, Torn and Harte 2006).

Based on photosynthetic physiology, it is likely that the additional C uptake beyond a threshold will limit the plant's ability to effectively uptake CO_2 (Dukes 2000). Additionally, the capacity of surface waters to take up anthropogenic CO_2 is decreasing as levels increase. These phenomena make concentrations of CO_2 more sensitive to natural and anthropogenic emissions (IPCC 2013). Many uncertainties remain and more research is needed to define the effect of natural sinks in the further reduction of CO_2.

Given this situation, mitigation and adaptation strategies aimed to address these challenges are being proposed. Mitigation strategies tackle the causes of climate change and adaptation attacks the effects of the climate change on humans and ecosystems (IPCC 2014a). Jacoby et al. (2014) define mitigation as actions that reduce human contributions of GHGs to the planet. IPCC (2014a) states that adaptation is the process of adjustment to actual or expected climate and its effects. Mitigation measures include lowering emissions of GHGs (CO_2, NO_2, and CH_4) and increasing the net uptake of CO_2 through land-use changes, like forestry.

These environmental threats can be mitigated if excess C is removed from the atmosphere, but according to the National Climate Assessment (NCA 2014), "Natural processes only remove roughly half of the current rate of emissions from human activities. Therefore, mitigation efforts that only stabilize global emissions will not reduce the overall atmospheric concentrations of C, but will only limit the rate of the increase. The same is true for other long-lived greenhouse gases." All of these statements indicate that humans have a significant role to play in addressing climate change. Their intervention is needed to reduce GHG emissions to safer levels and to stabilize the C cycle through C storage.

Direct Carbon Storage

Direct C storage refers to a set of processes designed to capture CO_2 from the atmosphere, and then store it in either woody material or in other more stable fractions, such as in soils or geological formations (Sedjo and Sohngen 2012). Lal (2004) identified four direct C sinks:

- forestation, where CO_2 is removed from the atmosphere via biological activity;
- aquifer storage, where CO_2 is injected into terrestrial aquifers and is trapped hydro-dynamically;
- deep-sea storage, where CO_2 is injected into the ocean at approximately 3,000 m., where it is believed to remain stable for the long term; and
- mineral carbonation, in which the CO_2 reacts with minerals to form solid carbonates.

The focus of this dissertation is on the first phenomenon, carbon storage by via plants. Here, direct plant C sequestration takes place when plants photosynthesize atmospheric CO_2 and store it as plant biomass. Subsequently, in forestation (tree-based) activities some of this plant biomass is fixed in woody materials while other biomass is indirectly sequestered as soil organic carbon (SOC) during decomposition processes (Meyer and Tyrchniewicz 1996, Follett 2001, Burras et al. 2001). The accumulation of C fixed through agronomic, forestry, and conservation practices ultimately leads to a net gain in C fixation in soils (Follett 2001).

Biological uptake and storage in woody plant material is one way to mitigate GHG emissions (IPCC 2000a). In temperate zones, sustainable agriculture, reforestation, afforestation, and agroforestry systems (AFS) represent potential C sinks (Brandle et al. 1992a, Follett 2001, Albrecht and Kandji 2003, Nair and Nair 2003, Palm et al. 2005, IPCC 2007b, Jose et al. 2012).

Avoided C Emissions or Indirect C Storage

Avoided or reduced emissions refer to the estimate of C equivalent emissions that could have been released if a particular activity or intervention had not been carried out (High and DeYoung 2011, Draucker 2013, CDP n.d.). In agriculture, these avoided emissions result from the reduced use of energy for planting and growing a crop; producing and using fertilizers and pesticides, clearing roads of snow during winter, and heating and cooling homes (DeWalle and Heisler 1988). Any practice that reduces the amount of fossil fuel usage will result in avoided CO_2 emissions (USEPA 2014a).

Emissions avoidance is the most effective C management strategy to achieve atmospheric CO_2 stabilization and a subsequent decline of atmospheric CO_2 (Global Carbon Project 2008). Energy efficiencies through reduced energy consumption, renewable energy use, cleaner energy production, and switching to fuels with lower carbon contents are current strategies to reduce CO_2 emissions (USEPA 2014b).

Trees and wood waste are also being used as alternative sources of energy. Biomass from trees is suitable to produce heat, power, and transportation fuels (Kort and Turnock 1998). Net CO_2 emissions from a unit of electricity generation from bio-energy are 10 to 20 times lower than from fossil fuel based electricity generation (Kort and Turnock 1998).

Incorporating trees into the farm system provides additional benefits. Field windbreaks result in fewer acres being farmed which means a reduction in fuel consumption and a reduction of C emissions (Brandle et al. 1992). Fewer acres farmed reduces fertilizer and pesticide inputs, thus reducing the off-farm carbon impact (Brandle et al. 1992). Trees around buildings, rural and urban homes reduce the amount of fossil fuel required for heating and cooling (Mattingly et al. 1979, DeWalle and Heisler 1988, Brandle et al. 1992, Akbari et al. 1997, Kort and Turnock 1999). Depending on climatic zone; building size, structure and age; and the type of energy consumed protecting these structures can provide significant savings (Brandle et al. 1992).

The Role of Agriculture in Contributing to GHG Production and Mitigation

Agriculture has been identified as one of the anthropogenic activities that produce substantial amounts of GHGs (Barker et al. 2007, Johnson et al. 2007) as shown in Figure 2-1. Burning fossil fuels is the leading cause of anthropogenic GHG emissions into the atmosphere in the form of CO_2 (Tinker et al. 1995) see Figure 2-2.

Besides emitting CO_2, the rate of methane (CH_4) emissions from farming operations has doubled over the last 25 years, increasing at a rate of 1% per year (Snyder et al. 2009) with 70 - 90% coming from biotic sources (Bouwman 1990). Atmospheric concentrations of nitrous oxide (N_2O) are reported to have increased from 270 ppb during the preindustrial era to 325 ppb in 2014 (USEPA 2014a). At the global, regional, and local scale, agriculture is considered the largest source of anthropogenic N_2O and CH_4 (Pitesky and Stackhouse 2009); contributing 52% of global methane and 84% of global nitrous oxide emissions (Desjardins 2010).

Agricultural systems continue to add C to the atmosphere by using fossil fuels in machinery, using chemicals and other inputs that are energy intensive to manufacture, and cultivating soil, which results in a dynamic release of C (IPCC 2000b, Pretty and Ball 2001, Lal 2004). A global analysis of soil C loss following cultivation of forests or grasslands shows a 20% reduction of the initial soil organic carbon (SOC), or approximately 1,500 g m^{-2} in the top 0.3 m of the soil (Mann 1986). Davidson and Ackerman (1993) estimated 30% SOC loss within 20 years following cultivation, with the greatest loss in the first 5 years.

Conversely, agriculture is also an accumulator of C; offsetting loses when the organic matter (OM) accumulates in the soil or when aboveground woody biomass acts either as a semi-permanent sink or is used as an energy source (Paustian et al. 1995, Buyanovsky and Wagner 1998, Pretty and Ball 2001, Freibauer et al. 2004, Lal 2004, Smith et al. 2008).

Long-term rates of C storage are reported in different agroecosystems ranging from a low of 0.2 g C m^{-2} yr^{-1} in some polar deserts to more than 10 g C m^{-2} yr^{-1} in some forest ecosystems (Schlesinger 1999). Most agroecosystems have the potential to store C. Pastures, agroforestry and forest ecosystems tend to lead in soil C storage, depending on the region. In some regions, large agricultural areas represent a considerable potential for enhancing the rate of C sequestration through management activities that reverse the effects of cultivation on soil organic carbon (SOC) pools (Post 2002). In these cases, refilling depleted soil C pools via woody biomass production may result in much higher rates of SOC storage than the accumulation of passive soil C as documented by Schlesinger (1999).

These results suggest that enhancing the transfer of atmospheric C into soil using specific soil management practices may help mitigate climate-change impacts. However, this concept only applies when the additional C remains stored and is not rapidly released (Freibauer et al. 2004, Trumbore and Czimczik 2008). For this reason, it is essential to estimate the duration of storage or mean residence time (MRT) of C in agricultural soils (Morris et al. 2010).

Building a Climate Smart Agriculture

Addressing the global challenges of climate change, food security, and poverty alleviation requires enhancing the adaptive capacity and mitigation potential of agricultural landscapes throughout the world (Harvey et al. 2013). Agriculture must simultaneously address three interwoven challenges: food security, adaptation to climate change, and mitigation of climate-change impacts (FAO 2010, Foresight 2011, Beddington et al. 2012).

The Climate Smart Agriculture (CSA) approach was proposed by FAO (2010) as a strategy to tackle these social and environmental challenges. Climate Smart Agriculture is defined as the integration of the three dimensions of sustainable development to address food security and climate challenges: social, economic, and environmental (FAO 2010).

Several management strategies hold particular promise for simultaneously achieving these three goals of production, adaptation and mitigation at the plot and farm scale (CSA 2014). For example, soil conservation practices, such as conservation tillage can increase soil health and protect the soil from extreme weather events (Delgado et al. 2011).

Many “climate-smart” practices that address both adaptation and mitigation goals are already well-known and fall under the greater umbrella of conservation agriculture, agroforestry, sustainable agriculture, evergreen agriculture, silvopastoral systems, sustainable land management, eco-agriculture, or best-management practices (FAO 2010, Garrity et al. 2010). Still, a greater understanding of these practices and their adoption rate is required to produce reliable information and technologies that land managers will embrace (CSA 2014).

The Role of Agroforestry Systems in the Climate Smart Agriculture Approach

Agroforestry systems (AFS) are defined as technologies where woody perennials (trees, shrubs, palms, and bamboos) are deliberately grown on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence (Lundgren and Raintree 1982, IPCC 2000a). Integrating woody plants into crop and livestock systems, if properly designed and located, can improve soils, increase water and air quality, and enhance wildlife habitat, while at the same time supporting sustainable production (Kursten 2000). While agroforestry plays a significant role in mitigating the concentration of GHGs, it also helps farmers to adapt to climate change (Verchot et al. 2007, Schoeneberger et al, 2012). For these reasons, agroforestry is included as a management option for C sequestration under the Clean Development Mechanisms of the Kyoto Protocol (Watson et al. 2000, Smith et al. 2007, IPCC 2007b) and CSA approach (FAO 2010).

In North America, there are five main categories of agroforestry practiced: riparian forest buffers, windbreaks, alley cropping, silvopasture, and forest farming. These categories vary according to the structure and function of their components (Table 2-1). By incorporating agroforestry practices into agricultural operations, the amount of C that can potentially be sequestered is greater than that achievable by crops alone (Nair et al. 2009a, Morgan et al. 2010). At a global scale this potential ranges from 0.29 to 15.21 Mg ha^{-1} yr^{-1} (Nair et al. 2009b) while conservation practices on croplands in the United States range from 0.1 (Lal et al. 1998) to 2.15 Mg ha^{-1} yr^{-1} (Franzluebbers 2010). The greatest dividend of C sequestered via agroforestry practices comes from the increased soil organic carbon (SOC) belowground and the woody biomass, above- and belowground (IPCC 2000a, Montagnini and Nair 2004).

Although C sequestration through afforestation and reforestation has long been considered useful in climate-change mitigation (IPCC 2000a), agroforestry offers distinct advantages. Agroforestry practices enhance the capability of farmers to increase soil health, improve air and water quality, increase local biodiversity, reduce weeds and pests, reduce pressure on natural forests, and enhance welfare for livestock (Brandle et al. 1992, Makundi and Sathave 2004, Gold and Garret, 2009, Murthy et al. 2013, Poch and Simonetti 2013). Likewise, these systems can enhance the resilience of farms coping with extreme events (Schoeneberger et al. 2012, Verchot et al. 2007). Agroforestry, when used to intensify agriculture production, provides additional indirect benefits by: 1) reducing the farm's use of fossil fuels, 2) reducing the energy used for heating and cooling homes and other buildings, 3) reducing the inputs applied to crops and livestock, and 4) providing more diversity for wildlife habitat (Brandle et al. 1992, Pretty and Ball 2001, Gordon et al. 2009). Likewise, diversifying the crop production system to include a significant tree component may buffer the income risks associated with climatic variability (Verchot et al. 2007).

Globally, agroforestry offers important opportunities to create synergies between adaptation and mitigation actions (FAO 2010). Simulation models developed to evaluate the potential of agroforestry practices to store C suggested that there are approximately 85 to 1,215 M ha in agroforestry practices in Africa, Asia, and the Americas (Dixon 1995). The IPCC projected that 630 M ha of unproductive cropland and grassland could be converted to agroforestry by 2010 (IPCC 2000a) and could potentially sequester 1.43 and 2.15 Tg CO_2 yr^{-1} by 2010 and 2040, respectively. Kumar et al. (2014) estimated that 1,023 M ha are currently under agroforestry worldwide.

The global potential to sequester C was estimated at 1.1 to 2.2 Gt (1 Gt = 1,000 Tg) of C per year over 50 years (Dixon 1995). Using values and total land area planted to agroforestry (1,215 M ha) from Dixon (1995), a C sequestration potential of 1.9×10^3 Tg C yr^{-1} over 50 years was calculated (MIT 2013). These estimates are close to the 1.6 to 1.8×10^3 Tg C yr^{-1} lost due to deforestation and other agricultural activities (Lal and Bruce 1999). However, in order to increase the amount of C sequestration and contribute effectively to atmospheric CO_2 reduction, new agroforestry projects must be implemented on the remaining 3,953 M ha of cropland and pastures in the world (MIT 2013).

In North America, potential C sequestration rates of AFS for above- and belowground biomass components were estimated at 2.6 Mg C ha^{-1} yr^{-1} for riparian forest buffers, 3.4 Mg C ha^{-1} yr^{-1} for alley-cropping systems, 6.1 Mg C ha^{-1} yr^{-1} for silvopastures, and 6.4 Mg C ha^{-1} yr^{-1} for windbreaks (Udawatta and Jose 2011). Additionally, 630 M ha of unproductive croplands and grasslands could be converted to agroforestry, representing a C sequestration potential of 0.4 Tg C yr^{-1} by 2010 and 0.6 Tg C yr^{-1} by 2040 (IPCC 2007b, Jose 2009). These estimates were derived from 1.69 M ha under riparian buffers, 17.9 M ha (10% of total cropland) in alley cropping, and 78 M ha of silvopasture (23.7 M ha or 10% of pasture land, and 54 M ha of grazed forests) (Nair and Nair 2003, Udawatta and Jose 2011). These systems have the potential to store 4.7, 60.9, 474 and 8.79 to 58 Tg C yr^{-1}, respectively (Udawatta and Jose 2011).

Estimates of the C storage potential for agroforestry systems are shown in Table 2-2. Although there is little doubt about the potential of agroforestry to store C, their effectiveness is determined by local physical, ecological, and socio-economic factors (Nair and Nair 2003, Newaj and Dhyani 2008). Locally, the amount of C in any agroforestry system depends on the structure and function of different components within the specific system (Schroeder 1993, Albrecht et al. 2004). The interaction among these factors generates high levels of spatial heterogeneity among similar agroforestry practices at different locations (Montagnini and Nair 2004). Therefore, extrapolation across systems and locations can be misleading when applying local results on a global scale (Montagnini and Nair 2004, Sauer et al. 2007, Nair 2011b).

As with all agricultural management activities, agroforestry systems can function as both a source and sink of GHG (Dixon 1995, Montagnini and Nair 2004, Udawatta and Jose 2011, Eagle et al. 2012). Evidence from Dixon (1995), Chikowo et al. (2003) and Kandji et al. (2006), suggests that the type of agroforestry system greatly influences whether the components function as a source or sink and to what extent. For instance, Dixon (1995), Chikowo et al. (2004) and Kandji et al. (2006) show improved fallows and silvopastures as sources of NO_2 and CH_4, respectively. However, the net C equivalent in the aboveground and belowground biomass of an agroforestry system is generally much higher than the equivalent land use without trees (Albrecht and Kandji 2003, Schoeneberger 2009, Nair 2011a, Murthy et al. 2013). See Table 2-2.

In the case of riparian forest buffers in agricultural systems, these plantings can reduce excess NO_2 emissions through the uptake of N by trees (Bergeron et al. 2011), reduce the impacts from flood events (Wenger 1999), store C, prevent nutrient losses, and reduce erosion (Falloon et al. 2004). Similarly, planting biofuel crops on arable lands can potentially reduce nitrate losses (Udawatta et al. 2002) and soil erosion (Berndes et al. 2004, Börjesson and Berndes 2006). Incorporating a biofeedstock component into riparian buffer systems, where appropriate, can provide farmers with additional income as well as provide added GHG mitigation and water quality services (Schoeneberger et al. 2012).

Inventory data and field measurements of agroforestry within the US, and more broadly North America, are very limited (Perry et al. 2009). Carbon sequestration estimates reported above were made using a variety of broad assumptions. The inherent variability of C storage potential and the lack of uniform methodologies among the many estimates make statistical comparisons challenging (Jose 2009, Nair 2011b). Despite these difficulties, trends from the information at hand indicate that AFS will sequester C and favorably reduce CO_2 emissions (Sauer et al. 2007, Schoeneberger 2009, Nair et al. 2010, Nair 2011b, Eagle et al. 2012).

As one of several promising climate-change mitigation and adaptation tools that will be needed for agricultural lands under the uncertainty of climate change (CAST 2011), implementing agroforestry projects is justified for many reasons. First, an increase in soil C significantly benefits agricultural productivity and sustainability (Verchot et al. 2007, Nair et al. 2009b, Howlett et al. 2011, Hernandez-Ramirez et al. 2011, USDA 2013). Second, it is improbable that any single mitigation method can achieve CO_2 reduction targets, rather combining several management activities, including the perennial-based agroforestry practices, appears to be a more realistic way to achieve CO_2 reduction targets, especially under the uncertainties of climate change (Paustian et al. 1997, Nair 2011b). Third, as the sale of C through Clean Development Mechanisms (CDM) becomes more popular in the future, agroforestry systems will definitely have potential to provide economic revenue for farmers while working to improve the environment, especially in developing countries (Takimoto 2007). Integrated analysis of agroforestry shows that these systems can sequester C and potentially increase incomes of farmers around the world (Antle et al. 2007).

Windbreaks/Shelterbelts

Temperate agroforestry systems in North America encompass five categories of practices as cited in Table 2-1 (Brandle et al. 2009). Windbreaks (also referred to as shelterbelts) are particularly attractive as a GHG mitigation tool for C storage in agricultural lands (Schoeneberger 2009). This is because windbreaks take only a small portion of land out of production (3 – 5%) (Brandle et al. 2009), yet provide many other services that are valued by the landowner and society, such as enhanced production to make up for the land taken out of production, along with the co-benefits of C sequestration and avoided emissions (Schoeneberger 2009).

Windbreaks are linear arrays of trees and shrubs (Buck et al. 1999) that serve as barriers to reduce wind speed (Rosenberg 1983, Brandle et al. 2009). They usually consist of one or more rows of trees or shrubs planted on croplands or grazing lands to alter the local microclimate (Skidmore 1986, Brandle et al. 2009), protect crops and livestock (Brandle et al 2009), provide habitat for wildlife (Johnson et al. 2006, Rhodes 2012), and mitigate odors from farming operations (Tyndal and Colletti 2007).

Windbreaks reduce evapotranspiration (Caborn 1957, Brandle et al. 2009), wind erosion, and soil detachment by rain drops (Brandle et al. 1992b). They supply additional C sequestration in crop and livestock production systems, and increase energy savings in farm operations by reducing the amount of fossil fuel required to heat and cool homesteads and barns (Brandle et al. 1992b, Kort and Turnock 1999). Table 2-3 presents a review of studies that include a range of experimental designs, building types, landscaping, and climate conditions where energy savings for space heating and cooling ranged from 8% (Mattingly et al.1979) to 50% (Akbari et al. 1997).

Conservative energy savings ranging from 10 to 25% reported by USDA-Natural Resource Conservation Service (2006) need to be re-evaluated due to the technological advances in heating and cooling systems, home insulation, appliance types, and the concerns about climate change. This value, however, is close to the estimate of Moyer (1999) in Saskatchewan (Canada). Other studies have examined urban tree plantings and found similar ranges in cooling savings from well-placed trees ranging from 10 to 43% (McPherson 1994b).

Living snow fences are windbreaks planted to manage drifting snow. Depending on the design, living snow fences can reduce snow removal costs from adjacent roadways and improve road safety by trapping snow close to the shelterbelt (Tabler and Furnish 1982, Peterson and Schmidt 1984, Shaw 1988, Schmidt et al. 1994) or provide critical spring soil moisture for crops during the growing season by distributing snow relatively uniformly across a field (Scholten 1988). Incorrectly designed and placed windbreaks, on the other hand, can cause snowdrifts that can bury livestock during major storms (Robert et al. 1994). There are many reviews of windbreak performance in different scenarios around the world and the reader is referred to these for specific details on the functions of windbreaks (Caborn 1957, van Eimern et al.1964, Grace 1977, Brandle et al. 1988, Sun and Dickinson 1994, Brandle et al. 1988, Brandle et al. 1992, Burke 1998, CSIRO 2002, Udawatta and Jose 2011, Eagle et al. 2012).

Windbreaks have the most impact in semiarid areas where a major function is to protect soils from wind erosion (Brandle et al. 1988). The largest and most extensive shelterbelt-planting program in United States history was “the Prairie States Forestry Project.” In an effort to control the dust bowl the Federal Government initiated the planting of nearly 30,000 km of shelterbelts in six Great Plains States between 1935 and 1942 (U.S. Forest Service 1935, Droze 1977). Today, the growth and vigor of many of these trees have declined due to lack of management, spacing, aging, and invasion of undesirable, short-lived trees. Many others have been removed to accommodate various types of irrigation systems particularly center pivot systems.

As climate change concerns continue to rise, especially in regards to frequency and intensity of droughts, there is a renewed interest in windbreaks as both protection against wind erosion and as potential C sinks. Estimates of C sequestration by windbreaks are shown in Table 2-4. Most of these estimates are based only on the aboveground potion for different shelterbelt types in the United States and Canada. These estimates ranged from 0.68 Mg C km^{-1} for single-row shrubs (Brandle et al. 1992b) to 105 Mg C km^{-1} for single row hybrid poplar (*Populus deltoides* x *Populus nigra* Bartr. Ex. Marsh) (Kort and Turnock 1999).

Windbreaks contribute to the SOC pool, although at a limited spatial scale of the landscape (Udawatta and Jose 2011). Sauer et al. (2007) reported SOC concentrations under a Nebraska shelterbelt to be 55% more than that in the adjacent crop field. The shelterbelt treatment contained 12% more SOC in the 7.5 – 15 cm depth compared to the crop field. Overall, during a 35-year period, soils at 0 – 15 cm depth contained 3.71 Mg more SOC ha^{-1} in the shelterbelt area than the cultivated zone, which according to

Udawatta and Jose (2011) can represent an annual sequestration of 0.11 Mg ha^{-1}. Hernadez and Ramirez (2011) indicated that afforestation of cropland carried out through either shelterbelt or forest plantation caused substantial increases in SOC accrual (≥ 57%) in surface soil layers (to 7.5 or 10 cm deep) relative to conventionally, tilled cropping systems.

This increase of SOC in the shelterbelt is attributed to the absence of soil disturbance, increased litter accumulation, reduced erosion, and deposition of windblown material (Sauer et al. 2007). Further research is needed to identify the mechanism(s) responsible for the observed patterns of SOC within and adjacent to the shelterbelt, and to quantify the C in biomass and deeper soil layers (Sauer 2007).

Overall, the estimated C storage potential of different scenarios of windbreaks in the United States ranges from 2.9 to 11 Tg C ha yr^{-1} (Brandle et al. 1992a, USDA-NAC 2000, Nair and Nair 2003, Montagnini and Nair 2004, Udawatta and Jose 2011).

According to the scientific body of research on agroforestry, windbreaks are a practical way to store C on agricultural lands, but many questions remain. As pointed out by Schoeneberger et al. (2012), the spatial and temporal dynamics in the system require additional research and technology investment. Few papers have been written about C stocks in trees on cultivated lands (Sauer et al. 2007). Windbreaks lack explicit inclusion in any national inventory (Perry et al. 2009) making it difficult to accurately estimate the land area occupied by this practice and therefore its C storage potential.

Moving Farming Systems towards Carbon Neutral Farming

Integrated farming systems (or integrated agriculture) refer to agricultural systems that incorporate crops, domestic animals, trees, and non-conventional farming operations through nutrient cycling (Gold 1999, Dixon et al. 2001, Gliessman 2007, Behera and Sharma 2007, Francis and Porter 2011). The farm is conceived as a holistic or multi-functional land unit planned to maximize farm production and increase welfare of farm families (Gliessman 2007, Francis and Porter 2011), while at the same time improving the environment.

Integrating crops, livestock, and trees on farming operations is an agronomic, economic, and environmental challenge because of the complex interactions between components (Ong and Huxley 1996, Jose et al. 2004). Under holistic management, these types of production systems can achieve a more favorable net C footprint through crop residues, animal manures, soil conservation practices, crop rotations using intercropping and cover crops, and composting techniques (Altieri 2000). Studies in the United States show that alternative farming systems can achieve net returns comparable to those of conventional farms (Kraten 1979, Lockeretz et al. 1981, Goldstein and Young 1987). While yields are usually somewhat lower, alternative farms often compensate by lower input costs and greater net returns (Kraten 1979, Lockeretz et al. 1981). Studies comparing organic and conventional grain production systems show organic farming to be more sustainable (Kraten 1979, Lockeretz et al. 1981, Pimentel et al. 1984, Bolton et al. 1985, Reganold et al. 1987, Reganold 1988, Wells et al. 2000, Hepperly et al. 2006, Fliessbach et al. 2007, Teasdale et al. 2007, Küstermann et al. 2008).

Soil tillage, planting, and harvesting operations account for the greatest expenditure of fuel, labor, and input costs (USDA-NASS, 2014). Approaches to decrease these expenses are reduced soil tillage (Frye 1984), optimized fertilizer utilization and use efficiency (Cole et al. 1997), improved irrigation techniques, and enhanced solar drying. Likewise, considerable energy savings can come from intensive animal husbandry (Chianese et al. 2009, IPCC 2013). Cole et al. (1997) and Paustian et al. (1997) optimistically concluded that by integrating all of these possibilities, a 10 to 40% reduction in the current agricultural energy requirements might be achieved. Accordingly, theoretical U.S. fuel savings could be 0.01 to 0.05 Gt C year^{-1} (Paustian et al. 1997).

When trees are planted as agroforestry plantings on farms, the net GHG emissions in terms of C equivalents (CE) are substantially reduced. For a hypothetical farm of 250 ha, in Nebraska, the CO_2 sequestered under two management options (no-till with and without windbreaks) were estimate after 50 years to be 9.2 Gt under just no-till and 16.1 Gt under no-till with 5% of the land in windbreaks (the level of windbreaks generally prescribed for providing a good level of crop services) (Schoeneberger 2009).

Farming systems that include agroforestry create more complex and productive units. Choosing a set of best practices involves more than simply identifying practices to reduce emissions or those that make immediate economic sense. A more holistic farming approach includes: finding ways to understand and quantify the diverse services provided to farms by windbreaks, developing new ways to better quantify C balance on farms, and improving methods to compare practices on the basis of emissions per unit of output, rather than merely based on emissions by unit of area. Many methods and tools are needed.

Estimating the amount of emissions and potential of C storage on integrated farms is a challenging task and research in this field is still in its early stages. However, some advanced decision-support tools can facilitate research and reduce the investigation time. The combination of these tools and other data from different sources can play an important role in furthering the understanding necessary to conduct more comprehensive agroforestry research.

Denef et al. (2012) have reported on several science-based methods for quantifying GHG sources and sinks in agriculture and forestry. Decision-support tools to easily and accurately assess potential C contributions of agroforestry practices on farms are: Soil Changes under Agroforestry (SCUAF) (Young et al. 1998), COMET-VR 2.0 (Paustian et al. 2012), USAID FCC: Agroforestry tool (Casarim et al. 2010), Integrated Farming Systems (IFSM) (Rotz et al. 2011), COMET-Farm (USDA-NRCS 2012), and HOLOS (Krobel et al. 2013). Currently, some of these tools enable users to estimate C storage on farms with and without agroforestry systems, although these estimates are not without issue regarding accuracy.

COMET-Farm (http://cometfarm.nrel.colostate.edu/) is currently an entity-level, user-friendly tool for estimating the amount of C stored on agroforestry farms in the United States. This program places a value on a farm's C storage and under alternative management scenarios, including agroforestry. Amounts are then reported regarding GHG emissions between current management and future scenarios (USDA-NRCS 2012).

HOLOS (www.agr.gc.ca/holos-ghg) estimates whole-farm GHG emissions and carbon storage from lineal tree plantings. And finally, another user-friendly tool for estimating GHGs is IFSM (http://www.ars.usda.gov/services/software/download.htm?softwareid=5) which includes livestock, but it does not include agroforestry practices.

Overall, there is a high potential for windbreaks to help farm operations tackle the negative effects of climate change. Windbreaks can enhance the ability of farmers and agroecologists to deal with the uncertainties of a changing climate. To achieve these goals, cropping systems, tree species, management regimes, weather and soils may be effectively exploited if managers have the information and tools to wisely design their production systems. The first step is to develop farm-level analyses of potential windbreak scenarios that will tackle the social and environmental challenges of climate-change mitigation and adaptation based on the pillars of Climate Smart Agriculture.

Research Needs

According to Nair et al (2010), agroforestry has come of age during the past three decades. The amount of scientific data has expanded, yet the understanding of C storage and dynamics in AFS is still minimal. Similarly, a comprehensive study of the C storage potential of AFS on the North American continent is lacking in the literature (Udawatta and Godsey 2010). More research is necessary to more fully understand the performance of agroforestry as a GHG source or sink. The required inquiries include:

- Evaluating the emission and capture of nitrous oxides and methane (Nair et al. 2010), developing standardized methodologies for estimating and reporting above- and belowground C stocks (Nair, 2011b);
- Including C stored by agroforestry practices which are often left out in the current estimates (Albrecht et al. 2004);
- Analyzing soil C storage in layers deeper than 0.2 m (Morgan et al. 2010, Nair 2011b);
- Developing predictive models to simulate future climate and agroforestry systems (Albrecht and Kandji 2003);
- Assessing the dynamics of pests and diseases in agroforestry systems and developing more powerful methods to financially assess agroforestry practices (Takimoto 2007);
- Developing accurate biomass equations to reliably estimate the C storage potential of agroforestry systems (Zhou et al. 2014);
- Generating a wide range of agroforestry tree species for present and forthcoming climates;
- Developing decision-support tools and models (Jose and Gordon 2008, Schoeneberger et al. 2012).

From this list, one particular research need stands out - that accounting protocols and methodologies need to be developed for estimating C benefits from agroforestry plantings, especially at regional and national scales (Perry et al. 2005). Agroforestry-specific equations are very limited (Kort and Turnock 1999, Nair 2011a, Udawatta and Jose 2011, Czerepowicz et al. 2012) because there is a lack of the regional and U.S.-wide data sets required for developing agroforestry-specific models that go into making C estimates (Zhou et al. 2014). Compared to forests, agroforestry plantings have a more open environment, resulting in trees with greater branch production and specific gravity (Zhou et al. 2011). These differences indicate that existing forest-derived equations may not accurately estimate tree biomass (Zhou et al. 2011).

In summary, current understanding of C capture and storage by agroforestry is limited and many uncertainties remain about the level of their impact on C budgets. Wide ranging data on agroforestry practices are not available to estimate accurate levels of direct and indirect C sequestration in the United States (Eagle et al. 2012) More comprehensive research, information decision-support tools and models need to be developed (Jose and Gordon 2008). Although work remains regarding the research potential of agroforestry for North American agriculture, we need to be finding ways to use the science at-hand to assist those formulating land management decisions now (Schoeneberger et al. 2012).

References

Ainsworth, E.A. and Long, S.P. 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2, New Phytol 165:351-372.

Akbari, H., Kurn, D.M., Bretz, S.E., Hanford, W. and James, W. 1997. Peak power and cooling energy savings of shade trees, Energy and Buildings 25(2):139-148.

Albrecht, A. and Kandji, T.S. 2003. C sequestration in tropical agroforestry systems, Agriculture, Ecosystems & Environment 99:15-27.

Albrecht, A., Kandji, S. and Verchot, L. 2004. C sequestration in tropical agroforestry systems, World Agroforestry Centre (ICRAF), 7 p.

Altieri, M.A. 2000. Agro-ecology: principles and strategies for designing sustainable farming systems. http://nature.berkeley.edu/~miguel-alt/principles_and_ strategies.html (6/24/2015).

Antle, J.M., Stoorvogel, J.J. and Valdivia, R.O. 2007. Assessing the economic impacts of agricultural C sequestration: Terraces and agroforestry in the Peruvian Andes, Agriculture, Ecosystems and Environment 122:435-445.

Barker, T., Bashmakov, I., Bernstein, L., et al. 2007: Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the IPCC [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge University Press, Cambridge, UK and NY, USA. pp 25-93.

Bambrick, A.D., Whalen, J.K., Bradley, R.L., Cogliastro, A., Gordon, A.M., Olivier, A. and Thevathasan, N.V. 2010. Spatial heterogeneity of soil organic C in tree-based intercropping systems in Quebec and Ontario, Canada, Agroforest Syst 79:343-353.

Bates, C.G. 1945. Shelterbelt influences II: the value of shelterbelts in house heating, J. For 43(3):176-196.

Beer, J., Bonnemann, A., Chavez, W., Fassbender, H.W., Imbach, A.C. and Martel, I. 1990. Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) or poro (*Erythrina poeppigiana*) in Costa Rica, V. Productivity indices, organic material models and sustainability over ten years, Agroforest Syst 12:229-249.

Beddington, J.R., Asaduzzaman, M., Clark, M.E., Fernández-Bremauntz, A., Guillou, M.D., Jahn, M.M., Lin, E., Mamo, T., Negra, C., Nobre, C.A., Scholes, R.J., Sharma, R., Van Bo, N. and Wakhungu, J. 2012b. The role for scientists in tackling food insecurity and climate change, Agriculture and Food Security 1:10.

Behera, U.K. and Sharma, A.R. 2007. Modern concepts of agriculture: farming systems, Indian Agricultural Research Institute. 37 p.

Bentrup, G. 2008. Conservation buffers: design guidelines for buffers, corridors, and greenways, Gen. Tech. Rep. SRS-109. Asheville, NC: Department of Agriculture, Forest Service, Southern Research Station 110 p.

Berndes, G., Fredrikson, F. and Borjesson, P. 2004. Cadmium accumulation and Salix based phyto-extraction on arable land in Sweden, Agriculture, Ecosystems and Environment 103:207-223.

Bergeron, M., Lacombe, S., Bradley, R.L., Whalen, J., Cogliastro, A., Jutras, M.F. and Arp. P. 2011. Reduced soil nutrient leaching following the establishment of tree-based intercropping systems in eastern Canada, Agroforestry Systems 83:321-330.

Börjesson, P. and Berndes, G. 2006. The prospects for willow plantations for wastewater treatment in Sweden, Biomass and Bioenergy 30(5):428-438.

Bolton, H., Elliott, L.F., Papendick, R.I. and Bezdicek, D.F. 1985. Soil microbial biomass and selected soil enzyme activities: Effect of fertilization and cropping practices, Soil Biology and Biochemistry 17(3):297-302.

Bouwman A.F. 1990. Land use related sources of greenhouse gases: present emissions and possible future trends. Land use policy 7:154-164.

Brandle, J.R., Hintz, D.L. and Sturrock, J.W. 1988. Windbreak Technology, Elsevier Science Publishers, Amsterdam, 598 p.

Brandle, J.R., Wardle, T.D. and Bratton, G.F. 1992a. Opportunities to increase tree planting in shelterbelts and the potential impacts on C storage and conservation, in Sampson, R.N. and Dwight H. (eds.), Forests and Global Change, Opportunities for Increasing Forest Cover, Washington, DC, American Forests 1:157-176.

Brandle, J.R., Hodges, L., Tyndall, J. and Sudmeyer, R.A. 2009. Windbreak practices. In: Garrett HE (ed.) North American Agroforestry, an integrated science and practice, 2nd American Society of Agronomy, Madison, WI, pp 75-104.

Bouwman, A.F. 1990. Land use related sources of Greenhouse Gases: present emissions and possible future trends, Land use Policy 7:154-164.

Buck, L., Lassoie, J. and Fernandes, E. 1999. Agroforestry in sustainable agricultural systems, CRC Press, Boca Raton, FL, 416 p.

Burke, S. 1998. Windbreaks. Inkata Press, Port Melbourne, Vic. 128 p.

Burras, C.L., Kimble, J.M., Lal, R., Mausbach, M.J., Uehara, G., Cheng, H.H., Kissel, D.E., Luxmoore, R.J., Rice, C.W. and Wilding, L.P. Carbon Sequestration: Position of the Soil Science Society of America, Agronomy Publications and Papers, Paper 59, 6 p.

Buyanovsky, G.A., Wagner, G.H. 1998. C cycling in cultivated land and its global significance, Global Change Biology 4:131-141.

Caborn, J.M. 1957. Shelterbelts and microclimate, Forestry Commission, Bulletin No. 29, 135 p.

CDP, (Carbon Disclosure Project) n.d. Glossary of terms. https://www.cdp.net/Documents/Guidance/2012/Technical/glossary-of-terms.pdf (7/12/2015).

CAST, (Council for Agricultural Science and Technology). 2011. C sequestration and greenhouse gas fluxes in agriculture: Challenges and opportunities, Task force report No. 142, 106 p.

Casarim, F.M., Harris, N.L. and Brown, S. 2010. USAID Forest C Calculator: Data and Equations for the Agroforestry Tool: Winrock International. 14 p.

Chianese, D.S., Rotz, C.A. and Richard, T.L. 2009. Simulation of C dioxide emissions from dairy farms to assess greenhouse gas reduction strategies, Trans. ASAE 52:1301-1312.

Chikowo, R., Mapfumo, P., Nyamugafata, P. and Giller, K.E. 2003. Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe, Plant Soil 259:315–330.

Clark, D., Kim and E., Berry, C. and David, T. 1995. House characteristics and the effectiveness of energy conservation measures, Journal of the American Planning Association 61(3):386.

CSA, Climate Smart Agriculture. 2014. The Case for climate-smart agriculture, module 1 and 2. http://www.fao.org/climate-smart-agriculture/76491/en/ (7/1/2015).

CSIRO, (Commonwealth Scientific and Industrial Research Organization). 2002. National windbreaks program: current research on farm trees, 42(6):649-900.

Cole, C.V., Duxbury, J., Freney, J. Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, K. and Zhao, Q. 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture, Nutrient Cycling in Agroecosystems 49(1-3):221-228.

Czerepowicz, L., Case, B.S. and Doscher, C. 2012. Using satellite image data to estimate aboveground shelterbelt carbon stocks across an agricultural landscape, Agric. Ecosyst. Environ 156:142-150.

Davidson, E.A. and Ackerman, I.L. 1993. Changes in soil C inventories following cultivation of previously untilled soils, Biogeochemistry 20:161-193.

Delgado, J.A., Groffman, P.M., Nearing, M.A., Goddard, T., Reicosky, D., Lal, R., Kitchen, N.R., Rice, C.W., Towery, D. and Salon, P. 2011. Journal of soil and water conservation 66(4):118-129.

Denef, K., Paustian, K., Archibeque, S., Biggar, S. and Pape. S. 2012. Report of greenhouse gas accounting tools for agriculture and forestry sectors, Interim report to USDA, under Contract GS23F8182H, pp 44.

Desjardins, R.L. 2010. The impact of agriculture on climate change, Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada. http://nabc.cals.cornell.edu/ Publications/Reports/nabc_21/21_2_2_Dejardins.pdf (7/1/2015).

DeWalle, D.R. and Heisler, G.M. 1988. Use of windbreaks for home energy conservation, Agriculture Ecosystems Environment 22/23: 243-260.

Dixon, R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gases? Agroforestry Systems 31:99-16.

Dixon, J., Gulliver, A., Gibbon, D. and Hall, M. 2001. Farming systems and poverty. http://www.fao.org/docrep/003/y1860e/y1860e00.htm (7/1/2015).

Dossa, E.L., Fernandes, E.C.M., Reid, W.S. and Ezui, K. 2008. Above- and belowground biomass, nutrient and C stocks contrasting an open-grown and a shaded coffee plantation, Agroforest. Syst 72:103-115.

Draucker, L. 2013. Do We Need a Standard to Calculate “Avoided Emissions”? http://www.wri.org/blog/2013/11/do-we-need-standard-calculate-%E2%80%9Cavoided-emissions%E2%80%9D (7/12/2015)

Droze, W.H. 1977. Trees, prairies, and people—tree planting in the plains states, Texas Woman’s University Press, Denton, TX, 313 p.

Duguma, B., Gockowski, J. and Bakala, J. 2001. Smallholder cacao (*Theobroma cacao* L.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities, Agroforest Syst 51:177-188.

Dukes, J. 2000. Will the increasing atmospheric CO_2 concentration affect the success of invasive species? In: invasive Species in a Changing World. H. A. Mooney and R. J. Hobbs,(eds.) Island Press, Washington. http://web.ics.purdue.edu/~jsdukes/Dukes CO2_Invasion.pdf (7/1/2015).

Eagle, A.J., Henry, L.R., Olander, L.P., Haugen-Kozyra, K., Millar, N. and Philip, G.R. 2012. Greenhouse gas mitigation potential of agricultural land management in the United States: A Synthesis of the Literature, 2nd ed. Duke University, 68 p.

Falkowsky, P., Scholes, R. J., Boyle, E., Canadell, J., Canfields, D., Elser, J., Gruber, N., Hibbard, K., Linder, S., Hogberg, P., Mackenzie, F. T., Moore, B., Pedersen, T., Rosemthal, Y., Seltzinger, S., Smetacek, V. and Steffen, W. 2000. The global C cycle: A test of our knowledge of the Earth as a system, Science 290(13):291.

Falloon, P.D. and Smith P, Powlson D. 2004. C sequestration in UK arable soils: the case for field margins, Soil Use Management 20:240-247.

FAO, (Food and Agriculture Organization of the United Nations). 2008. The C sequestration potential in agricultural soils. http://unfccc.int/resource/docs/2008/smsn/igo/010.pdf (7/1/2015).

FAO, (Food and Agriculture Organization of the United Nations). 2010. "Climate-Smart" Agriculture policies, practices and financing for food security, adaptation and mitigation. http://www.fao.org/docrep/013/i1881e/i1881e00.pdf (7/1/2015).

Field, C.B., Boesch, D.F., Stuart, F., Gleick, P.H., Lubchenco, J., Overpeck, J.T., Parmesan, C., Root, T.L., Running, S.W. and Schneider, S.H. 2008. Ecological impacts of climate change. http://oceanservice.noaa.gov/education/pd/climate/teachingclimate/ecological_impacts_of_climate_change.pdf (7/1/2015).

Fliessbach, A., Oberholzer, H.R., Gunst, L. and Mäder, P. 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming, Agriculture, Ecosystems & Environment 118:273-284.

Follett, R.F. 2001. Soil management concepts and C sequestration in cropland soils, Soil Tillage Res 61:77-92.

Foresight. 2011. The future of food and farming: challenges and choices for global sustainability. Final Project Report, London, the Government Office for Science. 211 p.

Francis, C.A. and Porter, P. 2011. Ecology in sustainable agriculture practices and systems', critical reviews, Plant Sciences 30(1): 64-73.

Franzluebbers, A.J. 2010. Soil organic C sequestration with conservation agriculture in the southeastern USA: Potential and limitations. http://www.fao.org/ag/ca/C%20Offset%20Consultation/CMEETING/3FULLPAPERSBYCONSULTATIONSPEAKERS/PAPERFRANZLUEBBERS.pdf (7/1/2015).

Freibauer, A., Rounsevell, M.D.A., Smith, P. and Verhagen, J. 2004. C sequestration in the agricultural soils of Europe, Geoderma 122:1-23.

Frye, W.W. 1984. Energy requirements in no tillage, in: Phillips, R.E., Phillips, S.H. (eds.), No-tillage Agricultural Principles and Practices, Van Nostrand Reinhold, 127-151 pp.

Garrity, D.P., Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M. and Bayala, J. 2010. Evergreen Agriculture: a robust approach to sustainable food security in Africa, Food Security 2:197-214.

Gliessman, S. R. 2007. Agroecology: The ecology of sustainable food systems (2nd ed.). Boca Raton, FL: CRC Press /Taylor & Francis, 408 p.

Global Carbon Project. 2008. Carbon reductions and offsets. Coulter, L., Canadell, J.G., Dhakal, S. (eds.). Global Carbon Project Report No. 6, Canberra, 34 p.

Goldstein, W.A. and Young, D.L. 1987. An agronomic and economic comparison of a conventional and a low input cropping system in the Palouse, American Journal of

Alternative Agriculture 2(2):51-56.

Gold, M.A. and Garret, H.E. 2009. Agroforestry nomenclature, concepts, and practices, In: North American agroforestry an integrated science and practice, pp 45-55.

Gold, M.V. 1999. Sustainable Agriculture: Definitions and Terms. http://www.grida.no/geo/GEO/Geo-2-181.htm (7/13/2015).

Gordon, A.M., Thevathasan, N.V. and Nair, P.K.R. 2009. An agro-ecological foundation for temperate agroforestry, In: North American agroforestry an integrated science and practice, pp 25-41.

Grace, J. 1977. Plant response to wind, Academic Press, London, New York, 204 p.

Harrje, D.T., Buckley, C.E and Heisler, G.M. 1981. Building energy reductions: windbreak optimization, J. Energy Div., Am. Soc. Civ. Eng. 108(3):143-154.

Harvey, C.A., Chacon, M.; Donatti, C., et al. 2013. Climate-smart landscapes: opportunities and challenges for integrating adaptation and mitigation in tropical agriculture, Conservation Letters 7(2)77-90.

Hazlett, P.W., Gordon, A.M., Sibley, P.K. and Buttle, J.M. 2005. Stand C stocks and soil C and nitrogen storage for riparian and upland forests of boreal lakes in northeastern Ontario, For. Ecol. Manag 219:56-68.

Heisler, G.M. 1991. Computer simulation for optimizing windbreak placement to save energy for heating and cooling buildings, In: Trees and sustainable development: the third national windbreaks and agroforestry symposium proceedings, Ridge Town College, Ridge Town, OR, pp 100-104.

Hepperly, P., Douds, Jr. and Seidel, R. 2006. The Rodale farming system trial 1981-2005: long term analysis of organic and conventional maize and soybean cropping systems. In: Long-term field experiments in organic farming. Raupp, J., Pekrun, C., Oltmanns, M. and Köpke, U. (eds.). International Society of Organic Agricultural Research (ISOFAR), Bonn, pp 15-32.

Hernandez-Ramirez, G., Sauer, T.J. and Cambardella, C.A. 2011. Carbon sources and dynamics in afforested and cultivated Corn Belt soils, Soil Science Society, American Journal 75:216-225.

High, C. and Neeraj, G. 2011. Avoided Emissions from the Antrim Wind Project. http://antrim-wind.com/files/2012/03/RSG-Final-Avoided-Emissions-Report.pdf (7/12/2015).

Howlett, D.S., Mosquera-Losada, M.R., Nair, P.K.R., Nair, V.D. and Rigueiro-Rodríguez, A. 2011. Soil C storage in silvopastoral systems and a treeless pasture in northwestern Spain, Journal of Environmental Quality 40:825-832.

Houghton, R.A. 2007. Balancing the Global C Budget, Annual Review of Earth and Planetary Sciences 35:313-347.

Huang, J., Akbari H. and Taha, H. 1990. The wind shielding and shading effects of trees on residential heating and cooling requirements, ASHRAE Trans 96:1403-1411.

Huang, J.G., Bergeron, Y., Denneler, B., Berninger, F. and Tardif, J. 2007. Response of forest trees to increased atmospheric CO_2, Critical Reviews in Plant Sciences 26:265-283.

IPCC, (Intergovernmental Panel on Climate Change). 2000a. Land use, land use change, and forestry: special report. Intergovernmental Panel on Climate Change, on line at: http://www.ipcc.ch/pdf/special-reports/spm/srl-en.pdf (7/8/2015).

IPCC, (Intergovernmental Panel on Climate Change). 2000b. Emissions scenarios: A special report of working group III of the intergovernmental panel on climate change, https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf (7/13/2015).

IPCC, (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis. Contribution of the Working Group 1 to the Third Assessment Report of the IPCC. Climate Change 2001. http://www.grida.no/climate/ipcc_tar/wg1/pdf/wg1_tar-front.pdf (7/13/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2007a. Fourth Assessment Report, Climate Change 2007: Synthesis Report. http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms2.html (7/8/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2007b. Climate change mitigation, Contribution of Working Group III to the Fourth Assessment Report of the intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, pp 862.

IPCC, (Intergovernmental Panel on Climate Change) 2013. The physical science basis. Working group I contribution to the IPCC fifth assessment report. http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_TechnicalSummary.pdf (7/8/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2014a. Climate change 2014, synthesis report summary for policymakers. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf (7/8/2015).

IPCC, (Intergovernmental Panel on Climate Change) 2014b. Annex II. Glossary of terms. http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Glossary_FGD.pdf (7/8/2015).

Jacoby, H.D., Janetos, A.C., Birdsey, R.J., et al. 2014. Mitigation. Climate Change Impacts in the United States, In: The Third National Climate Assessment, Melillo, J. M., Terese, T.C., Richmond, T.C. and Yohe, G.W. (eds.), Global Change Research Program, pp 648-669.

Johnson, R.J., Beck, M.M. and Brandle, J.R. 2006. Windbreaks and wildlife. http://ianrpubs.unl.edu/live/ec1771/build/ec1771.pdf (7/8/2015).

Johnson, J.M.F., Franzluebbers, A.J, Weyers, S.L. and Reicosky, D.C. 2007. Agricultural opportunities to mitigate greenhouse gas emissions, Environmental Pollution 150:107-124.

Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview, Agroforestry Systems 76:1-10.

Jose, S., Gillespie, A.R. and Pallardy, S.G. 2004. Interspecific interactions in temperate agroforestry, Agroforestry Systems 61:237-255.

Jose, S., Gold, M.A. and Garrett, H.E. 2012. The future of temperate agroforestry in the United States. In: Agroforestry in the United States. http://greenlandsbluewaters.net/Future%20of%20Temperate%20AF%20in%20the%20US%20-%202012.pdf (7/8/2015).

Jose, S. and A.M. Gordon. 2008. Ecological knowledge and agroforestry design: an introduction. In: Toward Agroforestry Design, Jose, S. and Gordon, A.M. (eds.) Advances in Agroforestry 4:3-9.

Kandji, S.T., Verchot, L.V., Mackensen, J., Boye, A. and Van N.M. 2006. Opportunities for linking climate change adaptation and mitigation through agroforestry systems In: World Agroforestry into the Future, Garrity, D.P., Okono, A., Grayson, M. and Parrott, S. (eds.), World Agroforestry Centre (ICRAF), Nairobi, Kenya, pp. 113-121.

Kirby, K.R. and Potvin, C. 2007. Variation in C storage among tree species: Implications for the management of a small-scale C sink project, For. Ecol. Manage 246:208-221.

Kort, J. and Turnock, R. 1998. Annual accumulation in agroforestry plantations. http://www.agr.gov.sk.ca/19970123.pdf (7/8/2015).

Kort, J. and Turnock, R. 1999. C reservoir and biomass in Canadian prairie shelterbelts, Agroforestry Systems 44:175-189.

Krankina, O.N. and Dixon, R.K. 1994. Forest management options to conserve and sequester terrestrial C in the Russian Federation, World Resour. Rev 6:88-101.

Kraten, S.L. 1979. A preliminary examination of the economic performance and energy intensiveness of organic and conventional small grain farms in the Northwest, 316 p.

Krobel, R., Janzen, K.A., Beauchemin, K.A., Bonesmo, H., Little, S.M. and Mcallister, T.A. 2013. A proposed approach to estimate and reduce the environmental impact from whole farms, Act Agriculture Scand Section A, 9 p.

Kumar, B.M., George, S.J., Jamaludheen, V., Suresh, T.K. 1998. Comparison of biomass production, tree allometric and nutrient use efficiency of multipurpose trees grown in wood lot and silvopastoral experiments in Kerala, India, For. Ecol.

Manage 112:145-163.

Kumar, P., Singh, R.P., Singh, A.K. and Kumar, V. 2014. Quantification and distribution of agro forestry systems and practices at global level, Hort. Flora Research Spectrum 3(1):1-6.

Kursten, E. 2000. Fuel wood production in agroforestry systems for sustainable land use and CO_2 mitigation, Ecological Engineering 16:69-72.

Küstermann, B., Kainz, M. and Hülsbergen, K.J. 2008. Modeling C cycles and estimation of greenhouse gas emissions from organic and conventional farming systems, Renewable Agriculture and Food Systems 23:38-52.

Lal, R. and Bruce, J.P. 1999. The potential of world cropland to sequester carbon and mitigate the greenhouse effect, Env. Sci. & Policy 2:177-185.

Lal, R., Kimble, J.M., Follett, R.F. and Cole, C.V. 1998. The potential of U.S. croplands to sequester C and mitigate the greenhouse effect, Ann Arbor Press, Chelsea, MI, 244 p.

Lal, R. 2004. Soil C sequestration impacts on global climate change and food security, Science 304:1623-1627.

Lindroth, R.L., Kiney, K.K. and Platz, C.L. 1993. Responses of deciduous trees to elevated atmospheric CO_2: productivity, phyto-chemistry, and insect performance, Ecology 74(3):763-777.

Lockeretz W., Shearer, G. and Kohl, D.H. 1981. Organic farming in the Corn Belt, Science 211:540-547.

Lundgren, B.O. and Raintree, J.B. 1982. Sustained agroforestry, In: Nestel, B. (ed.). Agricultural Research for Development: Potentials and Challenges in Asia, ISNAR, The Hague, the Netherlands, pp 37-49.

Makundi, W.R. and Sathaye, J.A. 2004. GHG mitigation potential and cost in tropical forestry-relative role for agroforestry. Environment, Development and Sustainability 6:235-260.

Mann, L.K. 1986. Changes in soil C storage after cultivation, Soil Sci 142:279-288.

McPherson, E.G. 1994a. Using urban forests for energy efficiency and C storage, J. Forestry 94:36-41.

McPherson, E.G. 1994b. Energy-saving potential of trees in Chicago, In: Chicago's urban forest ecosystem: results of the Chicago urban forest climate project. Gen. Tech. Rep, NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA, 210 p.

Mattingly, G.E., Harrje, D.T. and. Heisler, G.M. 1979. The effectiveness of an evergreen windbreak for reducing residential energy consumption, ASHRAE Trans.

85(2):428-443.

Meyer, M. and Tyrchniewicz, A. 1996. Offsetting CO_2 emissions: Tree planting on the prairies, International Institute for Sustainable Development, pp 1-56.

MIT (Massachusetts Institute of Technology). 2013. C sequestration: capture and storage of C dioxide from Earth's atmosphere.http://igutek.scripts.mit.edu/ terrascope/index.php?page=index (7/8/2015).

Morgan, J.A, Follett, R.F., Allen, L.H., Grosso, S.D., Derner, J.D., Dijkstra, F, Franzluebbers, A., Fry, R., Paustian, K. and Schoeneberger, M.M. 2010. Carbon sequestration in agricultural land of the United States, J Soil Water Conserv 65:6-13.

Morris, S.J., Conant, R., Mellor, N., Brewer, E. and Paul, E.A. 2010. Controls on Soil C Sequestration and Dynamics: Lessons from Land-use Change, Journal of Nematology 42(1):78-83.

Moyer, R.L. 1999. Shelterbelt benefit to home heating cost, transactions of the ASAE 33(6):3-10.

Montagnini, F. and Nair P, K.R. 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems, Agroforestry Systems 61:281-295.

Murthy, I.K., Gupta, M., Tomar, S., Munsi, M., Tiwari, R, Hedge, G.T. and Ravindranath, N.H. 2013. Carbon sequestration potential of agroforestry systems in India, J. Earth Sci. Climate Change 4:131.

NCA, (National Climate Assessment). 2014. Climate Change Impacts in the United States: Mitigation. http://nca2014.globalchange.gov/report/response-strategies/mitigation (7/8/2015).

Nair, P.K.R. 2011a. Agroforestry systems and environmental quality: Introduction. Journal of Environmental Quality 40:784-790.

Nair, P.K.R. 2011b. Carbon sequestration studies in agroforestry systems: a reality-check, Agroforest. Syst 86:243-253.

Nair, P.K.R. 2004. Agroforestry: Trees in support of sustainable agriculture. In: Hillel, H., Rosenzweig, C., Powlson, D., Scow, K., Singer, M., Sparks, D. (eds.) Encyclopedia of Soils in the Environment, Elsevier, London, UK, pp 35- 44.

Nair, P.K.R., Nair, V.D. and Kumar B.M. 2010. Carbon sequestration in agroforestry systems, Adv. Agron 108:237-307.

Nair, P.K.R., Nair, V.D. Kumar, B. M. and Haile, S.G. 2009a. Soil C sequestration in tropical agroforestry systems: a feasibility appraisal, Environmental Science and Policy 12(8):1099-1111.

Nair, P.K.R, Kumar, B. and Nair, V.D. 2009b. Agroforestry as a strategy for C sequestration, J. Plant Nutr, Soil Sci 172:10-23.

Nair, P.K.R. and Nair, V.D. 2003. Carbon storage in North American agroforestry systems, In: Kimble, J., Heath, L.S., Birdsey, R.A. and Lal, R. (eds.), The Potential of U.S. Forest Soils to Sequester C and Mitigate the Greenhouse Effect, CRC Press LLC, Boca Raton, FL, pp 333-346.

Nair, P.K.R., Rao, M.R. and Buck, L.E. 2004. New vistas in agroforestry: A compendium for the 1st World Congress of Agroforestry, Advances in Agroforestry, 480 p.

Newaj, R. and Dhyani, S.K. 2008. Agroforestry for C sequestration: Scope and present status, Indian Journal of Agroforestry 10:1-9.

NOAA, (National Oceanic and Atmospheric Administration). 2015. Trends in atmospheric carbon dioxide. http://www.esrl.noaa.gov/gmd/ccgg/trends/ (7/8/2015).

Norby, R.J., DeLucia, E.H., Gielen, B., et al. 2005. Forest response to elevated CO_2 is conserved across a broad range of productivity, Proc. Natl. Acad. Sci. USA 102:18052-18056.

Palm, C.A., van Noordwijk, M., Woomer, P.L., Alegre, et al. 2005. Carbon losses and sequestration with land use change in the humid tropics. In: Slash and burn agriculture, The search for alternatives, Palm, A.., Vosti, S.A., Sanchez, P.A. and. Ericksen, J.P. (eds.). Columbia University Press, New York, USA. pp 42-63.

Palma, J.H.N., Graves, A.R., Bunce, R.G.H, Burgess, P.J., de Filippi, R., Keesman, J., van Keulen, H., Liagre, F., Mayus, M., Moreno, G., Reisner, Y. and Herzog, F. 2007. Modeling environmental benefits of silvoarable agroforestry in Europe, Agriculture, Ecosystems and Environment 119:320-334.

Pandey, D.N. 2002. Carbon sequestration in agroforestry systems, Climate Policy 2(4):367-377.

Parrotta, J.A. 1999. Productivity, nutrient cycling and succession in single and mixed-species stand of C*asuarina equisetifolia*, *Eucalyptus robusta* and *Leucaena leucocephala* in Puerto Rico, For. Ecol. Manage 124:45-77.

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., van Noordwijk, M. and Woomer, P.L. 1997. Agricultural soils as a sink to mitigate CO_2 emissions, Soil Use Management 13:1-15.

Paustian, K., Robertson, G.P. and Elliott, E.T. 1995. Management impacts on C storage and gas fluxes (CO_2, CH_4) in mid-latitude cropland and grassland ecosystems, In: Lal, R., Kimble, J., Levine, E., Stewart, B.A. (eds.), Soil Management and Greenhouse Effect, Advances in Soil Science, CRC Press, Boca Raton, FL, USA, pp 69-84.

Paustian, K., Schuler, J., K. Killian, A. and Chambers, et al. 2012. COMET2.0 – Decision support system for agricultural greenhouse gas accounting. In: Managing Agricultural Greenhouse Gases, Liebig, M. A., Franzluebbers , A. J. and Follett , R. F. (eds.), Academic Press, San Diego, CA, pp 251-270.

Peichl, M., Thevathasan, N.V., Gordon, A.M., Huss, J. and Abohassan, R.A. 2006. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada, Agroforest. Syst 66:243-257.

Perry, C.H., Woodall, C.W. and Schoeneberger, M.M. 2005. Inventorying trees in agricultural landscapes: toward an accounting of working trees, UNL Faculty Publications, Paper 10, 12 p.

Perry, C.H., Woodhall, C.W., Liknes, G.C. and Schoeneberger, M.M. 2009. Filling the gap: Improving the estimates of working tree resources in agricultural lands, Agroforestry Systems 75:91-101.

Peterson, C.T. and Schmidt, R.A. 1984. Outdoor scale modeling of shrub barriers in snow drifting, Agricultural and Forest Meteorology 31:167-181.

Pimentel, D., Berardi, G. and Fast, S. 1984. Energy efficiencies of farming: wheat, corn, and potatoes organically, In: Organic Farming: current technology and its role in a sustainable agriculture. Bezdicek, D.F. et al. (eds.), American Society of Agronomy, Madison, WI, pp 151-161.

Pitesky, M.E. and Stackhouse, K.R. 2009. Clearing the air: Livestock's contribution to climate change, Advances in Agronomy 103:1-40.

Poch, T.J. and Simonetti, J.A. 2013. Ecosystem services in human-dominated landscapes: insectivory in agroforestry systems, Agroforest Syst 87:871-879.

Polle, A., McKee, I. and Blaschke, L. 2001. Altered physiological and growth responses to elevated CO_2 in offspring from holm oak (*Quercus ilex* L.) mother trees with lifetime exposure to naturally elevated CO_2, Plant, Cell and Environment 24:1075-1083.

Post, M.W. 2002. Impact of soil restoration, management and land-use history in forest-soil carbon. In: the potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect, Kimble, J.M., Lal, R., Birdsey, R.A. and Heath, L.S. (eds.), CRC Press, USA. pp 191-198.

Pretty, J. and Ball, A. 2001. Agricultural Influences on C Emissions and Sequestration: A Review of Evidence and the Emerging Trading Options. Centre for Environment and Society, Paper 2001-03, University of Essex, UK, 30 p.

Rao, K.P.C., Verchot, L.V. and Laarman, J. 2007. Adaptation to climate change through sustainable management and development of agroforestry systems, Journal of SAT Agricultural Research 4(1):1-30.

Reganold, J.P. 1988. Comparison of soil properties as influenced by organic and conventional farming systems, American Journal of Alternative Agriculture 3(4): 144-155.

Reganold, J.P, Elliott, L.F. and Unger, Y.L. 1987. Long term effects of organic and conventional farming on soil erosion, Nature 330:370-372.

Rheinhardt, R.D., Brinson, M.M., Meyer, G.F and Miller, K.H. 2012. Carbon storage of headwater riparian zones in an agricultural landscape. Carbon Balance and Management. http://www.ncbi.nlm.nih.gov/pmc/articles /PMC3298783/pdf/1750-0680-7-4.pdf (7/8/2015).

Robert, L., Jairell, R.L. and Tabler, R.D. 1994. Model studies of snowdrifts formed by livestock shelters and pond embankments. 62th Western Snow Conference, New Mexico, 4 p.

Rhodes, T. 2012. Windbreaks for wildlife. http://www.ksre.ksu.edu/bookstore/pubs/MF805.pdf (7/8/2015).

Rosenberg, N.J., Black, B.L. and Verma, S.B. 1983. Microclimate: the biological environment. John Wiley & Sons, Chichester, 495 p.

Rotz, C.A., Corson, M.S., Chianese, D.S., Montes, F., Hafner, S.D. and Coiner, C.U. 2011. The integrated farm system model, reference manual, version 3.5. Pasture Systems and Watershed Management Research Unit Agricultural Research Service, USDA, http://www.ars.usda.gov/SP2UserFiles/Place/ 19020000/ifsmreference.pdf ((7/8/2015).

Roshetko, M., Delaney, M., Hairiah, K. and Purnomosidhi, P. 2002. Carbon stocks in Indonesian home garden systems: Can small holder systems be targeted for increased C storage? Am. J. Alt. Agr 17:125-137.

Sabine, C.L., Heimann, M., Artaxo, P., Bakker, D.C.E., Chen, A., Field, C.B., Gruner, N., Le Quere, C.L., Prinn, R.G., Richey, J.E., Romero, L.P., Sathaye, J.A. and Valentini, R. 2004. Current status and past trends of the global C cycle, In: The global C cycle: Integrating humans, climate, and the natural world, Field, C. B. and Raupach, M. R. (eds.), Island Press, Washington, DC, pp 17-44.

Sampson, R.N. and Kamp, M. 2005. Forest and agroforestry opportunities for C sequestration in the Big Sky, the Sampson Group, Inc. pp 12-13.

Sauer, T.J., Cambardella, C.A and Brandle, J.R. 2007. Soil C and tree litter dynamics in a red cedar–scotch pine shelterbelt, Agroforest Syst 71:163-174.

Sauer, T. 2007. The Dust Bowl's Prairie States Forestry Project: Model for an Effective Global Climate Change strategy? https://a-c-s.confex.com/crops/2007am/ techprogram/P33604.HTM (7/8/2015).

Scheffer, M., Brovkin, V. and Cox, P.M. 2006. Positive feedback between global warming and atmospheric CO_2 concentration inferred from past climate change, Geophy. Res. Lett 33:10702.

Schlesinger, W.H. 1999. Carbon sequestration in soils, Science 284:2095.

Schmidt, R.A, Jairell, R.L. and Tabler, R.D. 1994. Snow drifts and the aerodynamic drag on scaled model-shelterbelt, 62th Western Snow Conference, New Mexico, pp 167 -170.

Schoeneberger, M.M. 2009. Agroforestry: working trees for sequestering C on agricultural lands, Agroforestry Systems 75:27-37.

Schoeneberger, M.M., Bentrup, G., de Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., Zhou, X. and Current, D. 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture, Journal of Soil and Water Conservation 67(5):128-136.

Scholten, H. 1988. Snow distribution on crop fields, Agriculture, Ecosystems and Environment 22/23:363-380.

Schroeder, P. 1993. Agroforestry systems: integrated land use to store and conserve C, Climate Research 3:53-60.

Schuur, E.A.G., Bockheim, J., Canadell, J.G., et al. 2008. Vulnerability of permafrost C to climate change: Implications for the global C cycle, BioScience 58(8):701-714.

Sedjo, R. and Sohngen, B. 2012. Carbon sequestration in forests and soils, Annual Review of Resource Economics 4:127-144.

Sharrow, S.H. and Ismail, S. 2004. C and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA, Agroforest Syst 60:123-130.

Shaw D.L. 1988. The design and use of living snow fences in North America, Agr Ecosyst Environ 22/23: 351-362.

Shibu, J. and Sougata, B. 2012. Agroforestry for biomass production and carbon sequestration: an overview, Agroforestry Systems 86(2):105-111.

Skidmore, E.L. 1986. Wind erosion control. Climatic Change 9:209-218.

Smith, P., Martino, D., Cai, Z., Gwary, D., etal. 2008. Greenhouse gas mitigation in agriculture, Philosophical Transactions of the Royal Society, Biological Sciences 363:789-813.

Smith, P., Martino, D., Cai, Z., Gwary, D., et al. 2007. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society. http://rstb.royalsocietypublishing.org/content/363/1492/789 (7/8/2015).

Snyder, C.S., Bruulsema, T.W., Jensen, T.L. and Fixen, P.E. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems and Environment 133:247-266.

Stiling, P., Moon, D., Hymus, G. and Drake, B. 2004. Differential effects of elevated CO_2 on acorn density, weight, germination, and predation among three oak species in a scrub-oak forest, Global Change Biol 10:228-232.

Swamy, S. L. and Puri, S. 2005. Biomass production and C-sequestration of *Gmelina arborea* in plantation and agroforestry system in India, Agroforest Syst 64:181-195.

Sun, D. and Dickinson, G.R. 1994. Wind Effect on windbreak establishment in Northern Australia, Tree Planter's Notes 45(2):72-75.

Tabler, R.D. and Furnish, R.P. 1982. Benefits and costs of snow fences and Wyoming Interstate 80, Transport, Res. Rec, 860. Washington DC, National Academy of Sciences and National Research Council, Transportation Research Board p 13-20.

Takimoto, A. 2007. Carbon sequestration potential of agroforestry systems in the West African Sahel: an assessment of biological and socioeconomic feasibility, Ph.D. Thesis Dissertation at University of Florida, 184 p.

Takimoto, A., Nair, P.K.R. and Nair, V.D. 2008. Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel, Agri. Eco. Environ 125:159-166.

Teasdale, J.R., Coffman, C.B. and Mangum, R.W. 2007. Potential long term benefits of no-tillage and organic cropping systems for grain production and soil improvement, Agronomy Journal 99(5):1297-1305.

Tinker, P.B., Ingram, J. and Struwe, S.I. 1995. Effects of Slash-And-Burn Agriculture and Deforestation on Climate Change, Agriculture, Ecosystems and Environment 58:13-22.

Torn, M.S. and Harte, J. 2006. Missing feedbacks, asymmetric uncertainties, and the underestimation of future warming, Geophy. Res. Lett 33:10703.

Trumbore, S.E. and Czimczik, C.I. 2008. An uncertain future for soil C, Science 321:1455-1456.

Tyndall, J. and Colletti, J. 2007. Mitigating swine odor with strategically designed shelterbelt systems: a review, Agroforest Syst 69:45-65.

Udawatta, R.P. and Jose, S. 2011. Carbon sequestration potential of agroforestry practices in temperate North America. In: Carbon sequestration potential of agroforestry systems: opportunities and challenges, Kumar, B.M. and Nair, P.K.R. (eds.), Advances in Agroforestry, 17:17-42.

Udawatta, R.P. and Godsey, L.D. 2010. Agroforestry comes of age: putting science into practice. Agroforest. Syst 79:1-4.

Udawatta, R.P., Krstansky, J.J., Henderson, G.S. and Garrett. H.E. 2002. Agroforestry Practices, Runoff, and Nutrient Loss: A Paired Watershed Comparison. http://www.centerforagroforestry.org/research/rbcomparison.pdf (7/8/2015).

Usami, T., Lee, J. and Oikawa, T. 2001. Interactive effects of increased temperature and CO_2 on the growth of *Quercus myrsinaefolia* saplings. Plant, Cell and Environment 24:1007-1019.

USDA, (U.S. Department of Agriculture) 2013. Agroforestry. http://www.usda.gov/wps/portal/usda/usdahome?contentidonly=true&contentid=agroforestry.html (7/8/2015).

USEPA (U.S. Environmental Protection Agency) 2012. Inventory of U.S Greenhouse gas emissions and sinks: 1990-2010. http://epa.gov/climatechange/emissions/usinventoryreport.html (7/8/2015).

USEPA (U.S. Environmental Protection Agency) 2014a. Climate change impacts and adapting to change. http://epa.gov/climatechange/impacts-adaptation/index.html (7/8/2015).

USEPA (U.S. Environmental Protection Agency) 2014b. Overview of Greenhouse Gases: Emissions of fluorinated gases. http://epa.gov/climatechange/ghgemissions/gases/fgases.html (7/8/2015).

USDA-NAC (USDA National Agroforestry Center) 2000. C: Inside Agroforestry. http://nac.unl.edu/documents/insideagroforestry/2000fallwinter.pdf (7/8/2015).

USDA- NASS (USDA National agricultural Statistics Service) 2014. Crops production 2014, Summary. http://www.usda.gov/nass/PUBS/TODAYRPT/cropan15.pdf (7/8/2015).

USDA-NRCS (USDA Natural Resource Conservation Service) 2006. Conservation practices that save: Windbreaks/Shelterbelts. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_023631.pdf (7/8/2015).

USDA-NRCS (USDA Natural Resource Conservation Service) 2012. Comet Farm. http://cometfarm.nrel.colostate.edu/ (7/8/2015).

van Eimern, J., Karscho, R., Razumova, L.A. and Robertson, G.W. 1964. Windbreaks and shelterbelts, World Meteorological Organization, Technical Note No. 59, 188 p.

Verchot, L.V., Noordwijk, M.V., Kandji, S., Tomich, T. and Ong, C. 2007. Climate change: linking adaptation and mitigation through agroforestry, Mitigation and Adaptation Strategies for Global Change 12:901-918.

Walk, M.F., DeWalle, D.R. and Heisler. G.M. 1985. Can windbreaks reduce energy use in a mobile home? J. Arboric 11(6):190-195.

Wang, X.Z. 2007. Effects of species richness and elevated carbon dioxide on biomass accumulation: a synthesis using meta-analysis, Oecologia 152:595-605.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. and Dokken, D.J. 2000. Land use, land-use change, and forestry: a special report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, http://www.ipcc.ch/ipccreports/sres/land_use/003.htm (7/8/2015).

Wells, T., Chan, K.Y. and Cornish, P.E. 2000. Impact of different conventional and alternative farming systems on soil quality, Agriculture, Ecosystems and Environment 80:47-60.

Wenger, S. 1999. A review of the scientific literature on riparian buffer width, extent, and vegetation. http://www.rivercenter.uga.edu/research/tools/buffers/buffer_lit_review.pdf (7/28/2015).

Winjum, J.K., Dixon, R.K. and Schroeder, P.E. 1992. Estimating the global potential of forest and agroforestry management practices to sequester C, Water, Air, Soil Pollut 64:213-228.

Woodruff, N.P. 1954. Shelterbelt and surface barrier effects on wind velocities, evaporation, house heating, and snow drifting. Kansas Agric. Exp. Stn., Manhattan, pp 27.

Wotherspoon, A., Thevathasan, N.V., Gordon, A.M. and Voroney, R.P. 2014. Carbon sequestration potential of five tree species in a 25-year-old temperate tree-based intercropping system in southern Ontario, Canada, Agroforest. Syst 88:631-643.

Young, A., Menz, K.M., Muraya, P. and Smith, C. 1998. SCUAF - Version 4: A Model to estimate soil changes under agriculture, agroforestry and forestry, Australian Centre for International Agricultural Research, Technical Report Series No. 41, 49 p.

Zhou, X.H., Brandle, J.R, Awada, T.N., Schoeneberger, M.M. Martin, D.L. Xin, Y. and Tang, Z.H. 2011. The use of forest-derived specific gravity for the conversion of volume to biomass for open-grown trees on agricultural land, Biomass and Bioenergy 35:1721-1731.

Zhou, X., Schoeneberger, M.M., Brandle, J.R., Awada, T.N., Chu, N., Martin, D.L., Li, J., Li, Y. and Mize, C.W. 2014. Analyzing the Uncertainties in use of forest-derived biomass equations for open-grown trees in agricultural land, For. Sci 60: 1-18.

Figure 2-1. Share of different sectors in total anthropogenic GHG emissions for 2004 in the United States. (Redrawn from IPCC, 2007a).

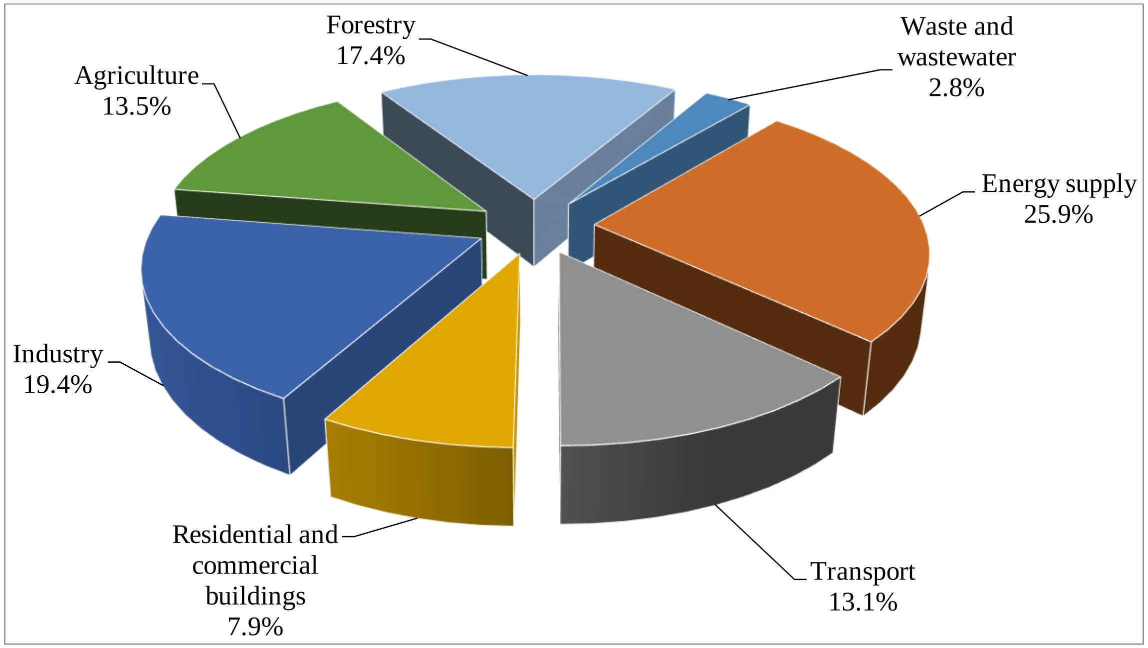
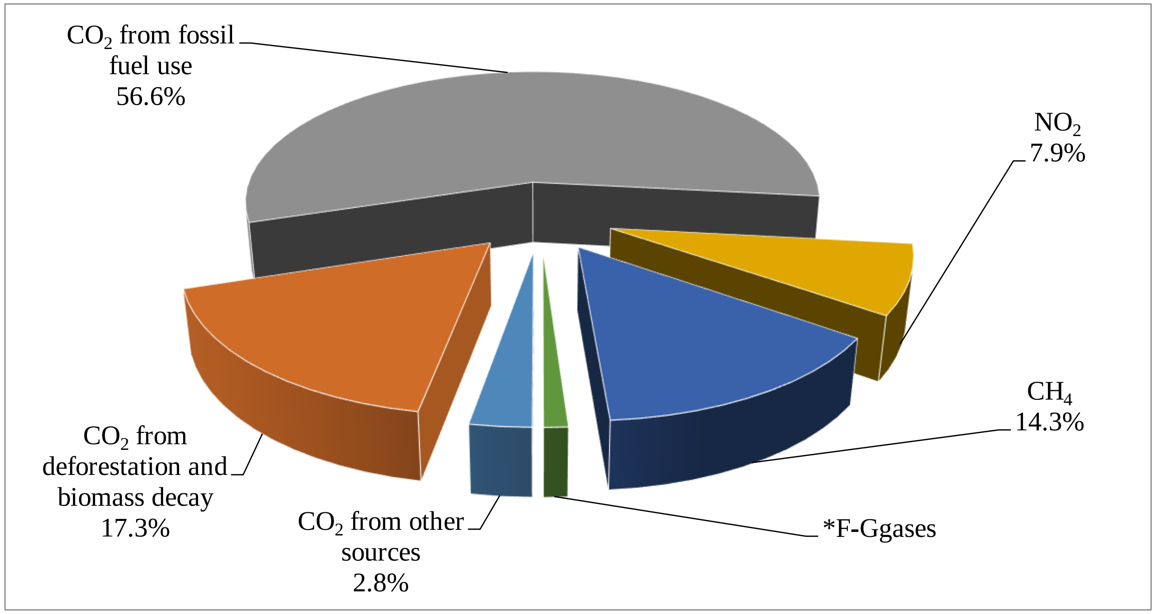


Figure 2-2. Proportion of different anthropogenic GHGs emissions for 2004 in the United States (Redrawn from IPCC, 2007a).



*F–gases= fluorinated gases

Table 2-1. Categories of agroforestry practices commonly established in the United States.

Practice.	Description	Primary Use
Riparian Forest Buffers	A combination of trees and other vegetative types established on the banks of streams, rivers, wetlands, and lakes.	• Reduce nonpoint source pollution from adjacent land uses • Stabilize streams • Protect aquatic and terrestrial habitats • Diversify income either through added plant production or recreation fees
Windbreaks (shelterbelts)	Linear plantings of trees and shrubs to forma barriers to reduce wind speed. Depending on the primary use, the windbreak may be specifically referred to as a crop or field windbreak, livestock windbreak, living snow fence, or farmstead windbreak.	• Control wind erosion • Protect wind-sensitive crops • Enhance crop yields • Reduce animal stress and mortality • Serve as barrier to dust, odor, and pesticide drift • Modify micro-climate around farmsteads • Manage snow dispersal • Reduce fuel use • GHG mitigation
Alley Cropping	Rows of trees planted at wide spacing while growing food, forage, or feedstock in the alleys.	• Stratify/diversify crops in time and space for greater production • Diversity income streams • Protect soils quality and reduce nutrient loss • Reduce fuel use • GHG mitigation

Source: CAST (2011)

Table 2-1. (con't)

Practice	Description	Primary Use
Silvopasture	Trees combined with pasture and livestock production	• Stratify/diversify crops in time and space for greater production • Diversity income streams • Reduce nutrient loss • GHG mitigation
Forest Farming	Natural stands whose canopies have been manipulated to grow high-value crops in the understory, such as mushrooms, decorative floral, and medicine herbs	• Stratify/diversify crops in time and space for greater production • Diversity income streams • GHG mitigation
Special Applications	Use of agroforestry technologies listed above to help solve special concerns such as disposal of animal wastes, filtering irrigation tail water while producing a short- or long rotation woody crop such as for biofeedstock	• Treat municipal and agricultural waste while generating additional products and income • Treat storm water issues • Use of the center pivot corners to generate additional habitat or income • Produce biofeedstock

Source: CAST (2011)

Table 2-2. Worldwide carbon storage potential of agroforestry systems.

Agroforestry/land-use system	Years	Carbon storage ($Mg\ ha^{-1}\ yr^{-1}$)	Source
Fodder bank, Segou (Mali W African Sahel)	7.9	0.3	Takimoto et al. (2008)
Live fence, Segou (Mali, W African Sahel)	-	0.6	Takimoto et al. (2008)
Tree-based intercropping (Canada)	13.0	0.8	Peichl et al. (2006)
Parklands, Segou, Mali (W African Sahel)	35.0	1.1	Takimoto et al. (2008)
Agrisiliviculture (Chattisgarh, central India)	5	1.3	Swamy and Puri (2000)
Silvopasture (W Oregon, USA)	11	1.1	Sharrow and Ismail (2005)
Cacao agroforests (Mokoe, Cameroon)	26	5.9	Duguma et al. (2001)
Cacao agroforests (Turrialba, Costa Rica)	5	10.3	Beer et al. (1990)
Cacao agroforests (Turrialba, Costa Rica)	10	11.1	Beer et al. (1990)
Shaded coffee (SW Togo)	13	6.3	Dossa et al. (2008)
Agroforestry woodlots (Kerala, India)	5	6.6	Kumar et al. (1988a)
Home and outfield gardens	23.2	4.3	Kirby and Polvin (2007)
Indonesian home gardens, (Sumatra)	13.4	8.0	Roshetko et al. (2002)
Mixed species stands, (Puerto Rico)	-	621	Parrotta (1999)
Agroforestry systems (world)	50	1.7	IPCC (2000b)
Agroforestry systems (World)	50	1.9	Dixon et al. (1995)
Agroforestry systems (world)	-	0.7	Eagle et al. (2012)
Agroforestry systems (world)	-	0.2 - 4.6	Dixon et al. (1994); Krankina and Dixon (1994), Schroeder (1993), Winjum et al. (1992), Pandey (2002)
Agroforestry slow growing trees (Europe)	-	0.1 – 0.57	Palma et al. (2007)
Agroforestry mod. fast growing trees (Europe)	-	0.54 – 0.9	Palma et al. (2007)
Agroforestry fast growing trees (Europe)	-	2.1 – 3.0	Palma et al. (2007)

Table 2-2. (con't)

Agroforestry/land-use system	Years	Carbon storage ($Mg\ ha^{-1}\ yr^{-1}$)	Source
Agroforestry systems (tropical)	-	1.5 – 3.5	Montagnini and Nair (2004), Watson et al. (2000)
Agroforestry systems (tropical)	-	3.1 – 4.3	Beer (1990)
Agroforestry (USA)	-	0.22 – 1.88	Eagle et al. (2012)
Riparian buffer/ mile (USA)	40	5.01 – 10.03	Schoeneberger (2008)
Riparian buffer/ mile (USA)	-	1.8	Hazlett et al. (2005)
Riparian buffer (USA)		1.87	Nair and Nair (2003)
Riparian buffer/ mile (USA)	-	4.8	Rheinhardt et al. (2012)
Agroforestry (USA)		0.72	Dixon et al. (1994)
Alley cropping (USA)	-	2.4 – 3.4	Udawatta and Jose (2011)
Alley cropping (USA)	-	4.5	Nair and Nair (2009)
Alley cropping (USA)		1.15	Nair and Nair (2003)
Alley cropping (USA)		1.15	Lal et al. (1998)
Alley cropping (USA)	-	0.5 – 13.2	Bambrick (2010)
Silvopasture (USA)	-	6.1	Udawatta and Jose (2011)
Silvopasture (USA)	-	5 – 10.1	USDA-NAC (2000)
Silvopasture (USA)	-	0.3	Nair and Nair (2003)
Silvopasture (USA)	-	2.6	Nair and Nair (2003)

Source: adapted from Nair et al (2009a)

Table 2-3. Effects of windbreaks on energy savings in the United States and Canada.

House type	Place	Energy demand Kw h^{-1}	Energy savings (%)	Author
Heavily shaded house	Sacramento	0.61 – 4.8	25 – 50	Akbari et al. (1997)
Houses with air conditioner	Phoenix	0.17	17	Clark and Berry (1995)
Houses with air conditioners and evaporative coolers	Phoenix	0.35	14	Clark and Berry (1995)
House without trees		3.55	-	Clark and Berry (1995)
Simulation for Cities	U.S.	0.15 – 0.5	2 – 10	Heisler (1991), Huang et al. (1987), (1990), McPherson (1994a), (1994b)
Average House	Great Plains	-	23 - 25	Bates (1945)
Average House	U.S.	-	27	USDA-NRCS (2006)
Average House	Kansas	-	15	Woodruff (1954)
Average House, single row windbreak		-	40	Mattingly (1977)
Air conditioning reduction	New Jersey	-	8	Mattingly et al. (1979)
Heating	New Jersey	-	3	Mattingly et al. (1979)
Air conditioning reduction	New Jersey	-	10	Harrje et al. (1981)
Heating energy	New Jersey	-	3	Harrje et al. (1981)
Heating energy	Pennsylvania	-	12	DeWalle and Heisler (1988)
Heating	Pennsylvania	-	0	Walk et al. (1985)
Typical northern US farm		-	10 – 30	DeWalle and Heisler (1988)
Wind speed reduction	Canada	-	17 – 25	Moyer (1999)
Urban home cooling		-	10 - 43	McPherson (1994b)

Table 2-4. Estimates of carbon storage potential for windbreaks/shelterbelts.

Agroforestry/land-use system	Years	Carbon storage Mg	Carbon storage Mg km^{-1}	Source
Aboveground deciduous trees (Canada)	-	0.11- 0.367	105	Kort and Turnock (1999)
Aboveground coniferous trees (Canada)	-	0.11– 0.19	24- 41	Kort and Turnock (1999)
Aboveground shrub (Canada)	-	-	11	Kort and Turnock (1999)
Green ash (Canada)	53	0.161.8	32	Kort and Turnock (1999)
Austrian pine (U.S.)	1	0.004	-	Zhou and Brandle in Sampson (2005)
Eastern red cedar(U.S.)	1	0.0015	-	Zhou and Brandle in Sampson (2005)
Manitoba maple (Canada)	52	0.178.6	34	Kort and Turnock (1999)
Hybrid poplar (Canada)	33	0.544.3	105	Kort and Turnock (1999)
Hybrid poplar (Canada)	13	0.12	-	Peichl et al (2006)
Hybrid poplar/tree/roots (Canada)	12	0.02	-	Gordon and Thevathasan (2009)
Poplar (Canada)	25	0.03	-	Wotherspoon et al. (2014)
Red oak (Canada)	25	0.03	-	Wotherspoon et al. (2014)
Walnut (Canada)	25	0.023	-	Wotherspoon et al. (2014)
Norway spruce (Canada)	25	0.03	-	Wotherspoon et al. (2014)
White cedar (Canada)	25	0.02	-	Wotherspoon et al. (2014)
Siberian elm (Canada)	37	0.201.9	40	Kort and Turnock (1999)
White spruce (Canada)	54	0.286.9	41	Kort and Turnock (1999)
Scots pine (Canada)	66	0.164	24	Kort and Turnock (1999)
Colorado spruce (Canada)	43	0.202	29	Kort and Turnock (1999)
Choke cherry (Canada)	33	0.403	20	Kort and Turnock (1999)
Villosa lilac (Canada)	23	0.335	17	Kort and Turnock (1999)
Buffalo berry (Canada)	20	0.312	15	Kort and Turnock (1999)

Table 2-4. (con't)

Agroforestry/land-use system	Years	Carbon storage Mg	Carbon storage Mg km^{-1}	Source
Above-ground single row conifer (Nebraska-USA)	20	-	9.14	Brandle et al. (1992)
Caragana (Canada)	49	0.516	26	Kort and Turnock (1999)
Sea buckthorn (Canada)	25	0.213	11	Kort and Turnock (1999)
Aboveground single row deciduous (Nebraska-USA)	20	-	5.41	Brandle et al. (1992)
Aboveground single row shrub conifer (Nebraska-U.S.)	20	-	0.68	Brandle et al. (1992)
Hybrid poplar (Canada)/ km	-	-	105	Kort and Turnock (1999)
Sea buckthorn/km	-	-	11	Kort and Turnock (1999)
Conifer	-	-	24 – .41	Kort and Turnock (1999)
Green ash	-	-	0.32	Kort and Turnock (1999)
Two rows shelterbelt soil organic carbon 15 cm depth (Nebraska U.S.) / ha	35	39.94	-	Sauer et al. 2007a
Hypothetic windbreak Sounders, Nebraska/ ha		2.95	-	Schoeneberger (2005)
Soil organic Carbon 0 to 0.075 m /ha	36	23.1	-	Brandle et al (2005)
Soil organic Carbon 0.075 to 0.15 m /ha	36	16.8	-	Brandle et al. (2005)

CHAPTER 3: DIRECT CARBON STORAGE BY WINDBREAK TREES ON AGRICULTURAL LANDS OF THE UNITED STATES

Abstract

Assessing carbon (C) capture and storage potential by the agroforestry practice of windbreaks has been limited. This is in part due to lack of suitable equations for estimating tree biomass C for the many species growing under the more open-grown conditions in agroforestry and across the of the United States where windbreaks are used. We analyzed the accuracy of 25 allometric models to estimate biomass storage by 16 tree species (eight conifer and eight hardwood species) located in nine regions. The forms of these models were evaluated using destructively sampled *Pinus ponderosa* from field windbreaks. The Jenkins' et al (2003) model and two new models were the most promising. Using the Jenkins' model, we estimated the biomass stored for the 16 tree species and converted these values to C in windbreaks projected out to 50 years in nine continental United States regions. Carbon storage potential in the windbreak scenarios ranged from 1.07±0.21 to 3.84±0.04 Mg C ha^{-1} year^{-1} for conifers species and from 0.99±0.16 to 13.6±7.72 Mg C ha^{-1} year^{-1} during 50 years for hardwood species. Estimated mean potentials across species and regions were 2.45±0.42 and 4.39±1.74 Mg C ha^{-1} year^{-1} for conifers and hardwoods, respectively. Such information enhances our capacity to better assess the C sequestering contributions of agroforestry in whole farm/ranch operations.

Keywords: climate change, agroforestry, allometric equations, tree biomass, carbon pools

Introduction

Agroforestry systems are an appealing strategy to increase the ecological and environmental services derived from agricultural lands (Rani et al. 2008). Included in these services are the capacity of these practices to mitigate greenhouse gases (GHGs) in agricultural operations by sequestering and storing carbon (C) along with providing climate adaptation services that add resiliency into our food systems and agricultural lands (FAO 2010, Schoeneberger et al. 2012).

In agroforestry systems, trees and shrubs can increase the amount of carbon stored above and belowground within agricultural operations compared to a monoculture crop field or pasture (Sharrow and Ismail 2004, Kirby and Potvin 2007, Kumar and Nair 2011). This contributes to reducing the atmospheric CO_2 while increasing the health of the soil (Nair et al. 2009, Jose et al. 2004). Additionally, these windbreaks, planted on just 3 to 5% of the agricultural lands, can reduce the emissions of CO_2 and NO_2 from farming (Brandle et al. 1992) while increasing crop yields (Kort 1988). Owing to the characteristics of this agroforestry practice to confer climate change adaptive and GHG mitigation services, windbreaks have been included as one of the tools in the Climate Smart Agriculture Approach (FAO 2010).

Designing field windbreaks to address the various issues from crop and livestock protection to GHG mitigation and other services is somewhat straightforward. The resulting biological, structural, spatial and environmental characteristics of their components, however, generate high levels of complexity that make quantification of actual and potential functions difficult (Raintree 1986). Extrapolation of results across individual plantings, settings and regions can be misleading (Nair 2011). Likewise, the lack of reliable biomass data from agroforestry systems (Jose et al. 2004, Nair 2011) makes it difficult to approximate windbreak contributions to the C budget. Currently, there are several efforts to develop consistent approaches to estimate C contributions of different management activities in agricultural operations. They range from compilation of accepted methodologies (Ogle et al. 2014) to incorporation into tools like COMET-FARM (http://cometfarm.nrel.colostate.edu/), a voluntary GHG reporting tool. Inclusion of agroforestry practices, like windbreaks, in these efforts requires that consistent and valid methods be developed so we can estimate the C storage potential of windbreaks anywhere they may be located.

The Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service (www.fia.fs.fed.us) provides an extensive and readily available Internet database for use in determining the extent, condition, volume, growth, and use of trees in United States forestlands (Brown et al. 1999, Woudenberg et al. 2010, USDA-FS 2014). This inventory can serve as a baseline to derive the above and belowground biomass and C storage potential for windbreak species. The main objectives of this study were to 1) assess the suitability of various allometric equations for estimating tree biomass in the more open-grown conditions of windbreak trees and 2) develop a method for easily estimating the C storage potential of windbreaks on agricultural lands in the United States.

Materials and Methods

Using an extensive query of FIA data and peer-reviewed articles, relevant allometric equations for the major ecoregions where windbreak use is applicable were collected (Appendix Table C-1) and compared for use with 16 tree species (8 hardwood and 8 conifers) commonly used in windbreak plantings (Table 3-1) and growing in different ecoregions (Figure 3-1). The 23 states in the continental United States selected for this study were grouped into nine regions (Figure 3-2) based on three main criteria: 1) located in almost identical Major Land Resource Areas (MLRA) (USDA-NRCS 2006), 2) sharing the same ecoregions (Bailey 1995, USDA-FS 2014), and 3) having trees periodically re-measured in the FIA data set (USDA-FS 2015).

Forest Inventory Data

The 16 tree species selected as potential for field windbreaks were queried in the FIA database (FIADB) version 5.1. The FIA inventory design, description of variables, field data collection, subsequent manipulation, uncertainties and the FIADB are available via the FIA website (USDA-FIA 2015). This query resulted in 276,849 tree records for the selected tree species in the identified ecoregions. Variables of specific interest to this study were the new and old diameter at breast height (dbh at 1.30 m), height (ht) and the derived Mean Annual Increments (MAIs). This resulting data set was then subsampled within the tree age range of 10 to 50 years.

Estimation of the Tree Biomass

From FIA data, tree MAI in diameter (MAID) was obtained with the formula (1):

$$\text{MAID} = \frac{\text{t.dia} - \text{t.prevdia}}{\text{ds.remper}} \qquad (1)$$

where t.dia symbolizes actual tree diameter, t.prevdia denotes the previous tree diameter, and ds.remper signifies the number of years between measurements.

The MAIDs were converted into biomass using twenty-five dbh-based allometric models (Appendix Table C-1). These models come from different tree species and locations. For this study, they were selected according to the age of the trees, diameter range, and component measured. Additionally, when a specific equation did not estimate belowground biomass, the Jenkins et al. (2003) ratio equation (3) was applied.

$$\text{ratio} = e^{\left(\beta_0 + \frac{\beta_1}{\text{dbh}}\right)} \qquad (3)$$

where ratio refers to the ratio of root component to total aboveground biomass (dry weight) for trees 2.5 dbh cm and larger and β_0 and β_1 identify the regression coefficients.

These twenty-five models were evaluated with destructively sampled *Pinus ponderosa* data from Montana (MT) and Nebraska (NE). Based on the form of these models (Spurr 1956, Prodan 1968, Loetsch et al. 1973), twelve allometric models to predict aboveground biomass were examined (Table 3-2). Although dbh is currently used for most local or regional biomass estimations, some researchers have suggested that both dbh and height should be included for larger-scale application (e.g., Honer 1971, Crow 1978). As such, we included height in our analysis of estimating biomass in these open-grown trees. Thus, for this study we developed two new models called “This study 1” and “This study 2” based on dbh and dbh, and height, respectively.

Statistical Analysis

Tree growth (MAIs per tree species) was compared among ecoregions within geographic regions using SAS 9.3. One-way ANOVA and the adjusted Tukey test were used to detect significant differences among ecoregions. The MAIs were converted to biomass by using specific allometric models.

A case study with destructively sampled *P. ponderosa*, using 12 models, was analyzed using R 3.1.1. The models were evaluated with Akaike's information criterion (AIC), predicted residual sum of squares (PRESS), adjusted R^2, and variance inflation factor (VIF). The Furnival index (Furnival 1961) was used when a transformed response variable was present. The information criteria prevented us from under- and over-fitting models (Nakamura et al. 2005) while variable transformation allowed us to test the residuals for normality, linearity and homoscedasticity, and to simplify the model (Kutner et al. 2004).

Generally, the information criteria analyzed agreed among them. See Table 3-5. Because information criteria used different approaches to evaluate the models, it was hard to decide which criterion was the best for some models. For this reason, a validation process (Kutner et al. 2004) was carried out to assess the accuracy of the optimum models, including the model from Jenkins et al. (2003). The regression model validation allowed us to decide whether the numerical results quantified from the relationships between variables, obtained from regression analysis, were acceptable as descriptions of the our data (Kutner et al. 2004). From these procedures, the Jenkin’s model was found to be the best model for predicting biomass of *P. ponderosa* in NE and MT.

After evaluating these models, we decided to use Jenkins' coefficients as the model for estimating biomass/C storage for the different species. The accuracy shown by use of Jenkins in this study, the national-scale application of Jenkins' coefficients (Jenkins et al. 2003), and the otherwise inconsistent and incomplete equations for estimating regional biomass for all windbreak trees, indicate that these coefficients are the best tool to develop biomass estimates for windbreak trees in the continental United States, at this time.

These biomass estimates were converted to C by using conversion factors of 0.48 and 0.51, for deciduous and conifers respectively (Lamlom and Sevidge 2003). These trees were grouped into deciduous and conifers tree species by region. When significant differences appeared among ecoregions, we selected the ecoregion with the "best" value for each species to avoid under and overestimation (Table 3.1). Finally, these values were projected to a hectare (ha) basis by using a one-row windbreak with a width of 3 m. This windbreak was monospecific, and, given the case, contained 814 deciduous, or 1,111 conifers, or 2,525 eastern red cedar (*Juniperus virginiana* L.), or 6,831 Russian olive (*Elaeagnus angustifolia* L.) trees per ha, respectively.

Sources of Error

Jenkins et al. (2003) reported some potential errors inherent in estimating forest biomass at large scales using published biomass equations. These errors included:

(1) Application of coefficients developed for one species (or group of species) to another species (or group of species).

(2) Sample trees and wood density samples were not representative of the target population because of factors such as size, range of sample trees, and stand conditions.

(3) Statistical error associated with estimated coefficients and form of selected equation.

(4) The standards, definitions, and methodology were inconsistent.

(5) Indirect estimation methods used that compound errors.

(6) The measurement and data processing that include errors.

It is nearly impossible to quantify all of these errors in a practical application, as cited by Baker et al. (2004). These error sources were noisy for this study. However, there are not locally developed biomass equations for all tree species in the 23 states and need to be addressed in the future when more data become available.

Results

Mean Annual Increment in Diameter for Typical Windbreak Tree Species

The MAIDs were generally not significantly different between ecoregions within geographic regions (Appendix Tables C-2). For deciduous, the largest variability in the MAI occurred between ecoregions of the Southeastern of the United States (Southern Plains, Appalachia and Delta States) (Appendix Table C-2.3, C-2.4 and C-2.5), while for softwoods, it occurred between the Corn Belt and Rocky Mountains North regions (Appendix Table C-2.2 and Table C-2.6). When MAIDs were not significantly different, biomass derivation was straightforward. When differences occurred, a mid-point value between these ranges was used to avoid over or underestimation of the tree biomass.

Suitability of Allometric Equations for Estimating Biomass

Comparing different allometric models using data from the destructively sampled ponderosa pine in NE and MT, five models fit the data reasonably well (Table 3-3). The models of Berkhout and Husch (n.d.) as cited by Loetscht et al. (1973) (Model # 10), Schumacher and Hall (1933) (Model # 12), “This study 1” (Model # 13), and “This study 2” (Model # 14) had the best fit. Although the Brenac (n.d.) model cited by Loetscht et al. (1973) (Model # 11) fit well, it was excluded from the next step because it had a high VIF value. An elevated value of VIF (>10) indicates that the predictor variables being considered in the regression model are highly correlated among themselves (Kutner et al. 2004).

The four models selected for further evaluation resulted in low values in all information criteria except for R square value. This did not agree with the other indices which suggest that the variable transformation process affected the R square criterion. The selected models included a square root response variable with and without height as explanatory variables and a log transformed response variable. Although the Furnival Index is preferred among other information criteria (Furnival 1961, Parresol 1999, Schreuder and Williams 1998) because it allows comparing models with different response variables and reduces the usual estimate of the standard error about the curve when the dependent variable is biomass (Parresol 1999), it was hard to choose the best model because their indices of the selected models were very close. Therefore, a validation test was carried out (Picard and Henry 2012, Kutner et al. 2014).

In the validation process, Jenkins' generalized model (Model # 14) was included to test the relationship between the overestimation reported for forest stands (Zhou and Hemstrom 2009, Domke et al. 2012, Chojnacky et al. 2014,) and the biomass estimates for open-grown trees. The models # 13 and #14 in Table 3-4 were the most accurate. These models included a square root transformed response variable with and without height. Figure 3-3 displays the predicted values of all five competing models. These results suggest that the square root transformed response variable, with dbh, and the combinations of dbh and height are good indicators of the *P. ponderosa* biomass. However, in the validation process (Table 3-4), Jenkins' model showed the lowest percentage of error (0.45%) and higher R square (98.7%).

The models #13, #14 and Jenkins, including the adjustment made by Chojnaky et al. (2014) to Jenkins were evaluated again, using data from FIA and from destructively sampled *P. ponderosa* in NE, MT, ecoregions 331, and 332 projected to 40 years. These estimates were consistent with predictions from models #13, #14 and Jenkins (Table 3-5). However, when compared to the adjusted Jenkins' models proposed by Chojnacky et al. (2014) the differences were significant, especially for trees with specific gravity greater than 0.40.

When comparing these predictions between states and ecoregions, these values were higher in NE than in other regions as showed in Table 3-5. These differences between the estimates possibly could have been a result of the way these trees were selected and/or the performance of these trees in different ecoregions. Trees in NE at age of 40 years showed a dbh ranging from 15.09 to 41.72 cm, which is higher when compared to MT (13.57 - 27.00 cm), ecoregion 331 (19.81 - 29.21 cm), and ecoregion 332 (16.76 - 25.91 cm).

Carbon Storage Potential for Windbreaks Trees in Different Regions

Carbon storage potential for windbreak trees as determined by the different allometric models showed high variability across regions as shown in Tables C-3 of the Appendix. Table 3-6 shows an example of the effect of allometric models in the variability of the C storage estimates. For this reason, we decided to use only Jenkins' coefficients to report the carbon storage estimates (Appendix Tables C-4). The mean C storage potentials across the regions were 4.39±1.7 for hardwoods and 2.45±0.4 Mg C ha^{-1} $year^{-1}$ for conifers (Table 3-7). In the Southern Plains region, hardwoods and conifers displayed the highest carbon storage potential, 7.80±4.43 and 1.86±0.02 Mg C ha^{-1} $year^{-1}$, respectively, over 50 years.

Discussion

The low variability of the tree's MAIs among ecoregions indicated that most species are growing within their natural range (Wells 1964, Burns et al. 1990, USDA-NRCS 2015) and that the ecoregions are commonly occupied by natural stands (USDA-NRCS 2015). The variations in some MAIs were due to extreme climatic conditions within regions (e.g. ecoregions 315 and 231 in southern Plains).

The assumption of MAIDs projected to 50 years was a reliable timeframe to estimate windbreaks biomass storage potential. Current thinking is that C sequestration will buy us time until other technologies come on board that can more effectively mitigate GHGs. It is stated that trees do not grow at a continuous rate (Lutz 2011). Instead, their cumulative growth curves (CGC) are sigmoidal until they level off. Stephenson et al. (2014) questioned the leveling off conclusion and proposed that tree biomass accumulation continuously increased with tree size, and that old growth trees can store more biomass than young trees. Oliver and Ryker (1990) indicated the same trend for *P. ponderosa*, which still increased its biomass after 200 years. Therefore, the MAIDs projection to 50 years was a reliable tool for estimates of potential windbreak tree biomass given their lifespan and growth curves (Spears 2000).

Biomass and the potential C storage derived from these MAIs in windbreaks were affected by their location even within relatively small geographic areas. These results are corroborated by the diversity of locations and climatic conditions where these species thrive (USDA-NRCS 2006, Birdsey 1992). Montagnini and Nair (2004) affirmed that these changes could occur even in areas smaller than the ecoregions used throughout this study. Brown et al. (1999) reported the same patterns in Oklahoma and Texas.

The different biomass equations influenced the resulting values of the C estimates in this study (Table 3-6). These differences in the relationship between MAIDs and biomass/C potential could be due to various reasons: the method for developing the allometric equations, the location effect (Arcano 2005, McHale et al. 2009), wood-specific gravity (Jenkins et al. 2003), site index (Balboa-Murias et al. 2006), and stand density (Litton et al. 2004).

Our model tests found that the evaluated models yielded promising results. Two of the proposed equations and two new ones gave the best accuracy for calculating total above-ground tree biomass for *P. ponderosa* in Nebraska and Montana and in ecoregions 331 and 332. Surprisingly, coefficients presented by Jenkins reported the highest accuracy for predicting tree biomass in the validation process. These results indicate that Jenkins' model for pines is very consistent and can be the first step for developing comprehensive estimates of biomass/C potential for open-grown trees for many species. However, the coefficients of Jenkins et al. (2003) modified by Chojnacky et al. (2014), did not necessarily produce values consistent with those from the destructively sampled data. Regarding stand-level estimates, most authors have reported an overestimation when using Jenkins et al. (2003). Seventeen percent overestimation was reported by Domke et al. (2012) when analyzing the major conifer species in Oregon. The same trend was reported by Zhou and Hemstrom (2009) when estimating aboveground tree biomass on forest land in the Pacific Northwest. Conversely, Zhou et al. (2014) found these derived forest –derived equations underestimated biomass in more open-grown windbreak trees.

In this study, the aforementioned overestimations agreed with the estimates for open-grown *P. ponderosa* tree in NE and MT, ecoregions 331 and 332, indicating a need for applying this same exercise to other regions to evaluate equation estimates. Although the sample size of 18 trees (12 trees for NE and 6 for MT), is a very limited representation of the windbreaks with *P. ponderosa,* these results can be used locally (Picard and Henry 2012). A larger sample size is required to account for the regional variability (Weiskittel et al. 2015). For now, our study results indicate the old Jenkins model will serve as a better baseline for making national estimates of biomass in windbreak trees compared to Jenkin's with the new Chojnacky's estimates.

This study highlights how regional predictions for biomass or C storage potential in the more open-grown windbreak trees will vary depending on the equations used. The standardization of the methodologies, the implementation of averaged equations across sites (Miles and Smith 2009), and the development of geographic weighted regression equations (Brunsdon et al. 1996) could be potential solutions for reducing this variability. Another driver of variability was the FIA database itself. Lack of standardized data and human error were among the bigger contributors to variability in biomass estimates; requiring a cleaning process before use in studies.

Estimates of carbon storage potentials per area basis are difficult to compare data reported by others because of the differences in assumptions and approaches used by each. However, our estimated values fit within the generalized range of 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$ as found by others (Brandle et al. 1992, Nair et al. 2009, Schoeneberger 2009). Having more standardized experimental procedures and data-gathering protocols that could be readily used for all regions would greatly improve the accuracy in making regional comparisons as well as then accumulating these values to generate national estimates (Udawatta and Jose 2011).

From the approach developed and used in this study, we found that the C storage potential for windbreaks over 50 years range from 1.07±0.21 to 3.84±0.04 Mg C ha^{-1} $year^{-1}$ for conifer and 0.99±0.16 to 13.6±7.72 Mg C ha^{-1} $year^{-1}$ for deciduous species. Because the magnitude of the differences among different allometric models our study suggested a high accuracy of the Jenkins' coefficients. The estimates for this process are the first step for making a comprehensive assessment of the coefficients of Jenkins used to estimate biomass for open grown trees.

Conclusions

Our recommendation for developing a better quantification technique for carbon sequestered in windbreaks is that it be based on Jenkins' coefficients. We found Jenkins' coefficients gave the best accuracy for estimating carbon storage potential for windbreaks in the continental United States. Using these coefficients would facilitate biomass/C estimations in the United States; reducing cost and time. We recognize that our data set was small and that more data are needed. Further, we recognize that local variability exists and that soil texture, maintenance, disease, insects, defoliation and other factors can affect results and increase uncertainties (Kort and Turnock 1999). Much work is still needed to determine the level and therefore need for developing more local evaluations.

A thorough understanding of how well trees may impact agricultural lands, especially windbreaks and their ability to overcome the impacts of climate change is essential as we develop management options (Gockowski et al. 2001). Depending on the tree species, location and windbreak arrangement the carbon storage potential can vary from one region to another. Developing accurate regional values can lead to a better understanding of the dynamics of these agroforestry systems in contributing to the global carbon pools.

References

Arcano, R. 2005. Allometric model development, biomass allocation patterns, and nitrogen use efficiency of lodge pole pine in the Greater Yellowstone ecosystem, Master of Science in Botany, University of Wyoming, 92 p.

Bailey, R.G. 1995. Description of the ecoregions of the United States, 2nd ed.(map)., US Department of Agriculture, US Forest Service, Washington DC, Miscellaneous Publication 1391:126.

Baker, T.R., Phillips, O.L., Malhi, Y., Almeida, et al. 2004. Variation in wood density determines spatial patterns in Amazonian forest biomass, Glob. Change Biol 10:545-562.

Balboa-Murias, M.A., Rodríguez-Soalleiro, R., Merino, A. and Álvarez-González, J.G. 2006. Temporal variations and distribution of carbon stocks in aboveground biomass of *Pinus radiata* and pine maritime pure stands under different silvicultural alternatives, For. Ecol. Management 237:29-38.

Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystem, USDA general technical report, http://www.nrs.fs.fed.us/pubs/gtr/gtr_wo059.pdf (7/1/2015).

Brandle, J.R., Wardle, T.D. and Bratton, G.F. 1992. Opportunities to increase tree planting in shelterbelts and the potential impacts on carbon storage and conservation. In: Sampson, R.N. and Dwight, H. (eds.), Forests and Global Change: Opportunities for Increasing Forest Cover, Washington, American Forests 1:157-176.

Brown, S.L., Schroeder, P. and Kern, J.S. 1999. Spatial distribution of biomass in forests of the eastern USA, Forest Ecology and Management 123:81-90.

Brunsdon, C., Fotheringham, A.S. and Charlton, M. 1996. Geographically weighted regression: a method for exploring spatial non-stationarity, Geographical Analysis 28(4):281-298.

Burns, R.M. and Honkala, B.H. (Tech. Coords). 1990. Silvics of North America: 1. Conifers; 2. Hardwoods, Agriculture Handbook 654.U.S. Department of Agriculture, Forest Service, Washington DC, 2:877.

Chojnacky, D.C., Heath, L.S. and Jenkins, C.J. 2014. Updated generalized biomass equations for North American tree species, Forestry 87:129-151.

Chojnacky, D.C. 2002. Allometric scaling theory applied to FIA biomass estimation. In: Proceedings of 3rd annual forest inventory and analysis symposium. McRoberts R.E., Reams G.A., Van Deusen P.C. and Moser J.W. (eds.), Traverse City, MI. Gen. Tech. Rep. NC-230, St. Paul, MN: USDA, Forest Service, North Central Research Station, pp 96-102.

Comeau, P.G. and Kimmins, J.P. 1989. Above- and belowground biomass and production of lodgepole pine on sites with differing soil moisture regimes, Canadian Journal of Forest Research 19(4):447-454.

Crow, T.R. 1978. Biomass and production in three contiguous forests in northern Wisconsin, Ecology 59:265-273.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A. and McRoberts, R.E. 2012. Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates, Forest Ecology and Management 270:108-116.

FAO, (Food and Agriculture Organization of the United Nations). 2010. "Climate-Smart" Agriculture policies, practices and financing for food security, adaptation and mitigation. http://www.fao.org/docrep/013/i1881e/i1881e00.pdf (7//1/2015).

Furnival, G.M. 1961. An index for comparing equations used in constructing volume tables, Forest Science 7:337-341.

Gockowski, J., Nkamleu, G.B. and Wendt, J. 2001. Implications of resource-use intensification for the environment and sustainable technology systems in the Central African Rainforest In: Tradeoffs or Synergies? Agricultural intensification, economic development and the environment, Lee, D.R. and Barrett, C.B. (eds.). CAB International, Wallingford UK, pp 197 -219.

Harlow, W.M., Harrar, E.S., Hardin, J.W. and White, F.M. 1991. Textbook of dendrology. 7th ed, McCraw-Will, New York, 501 p.

Honer, T. 1971. Weight relationships in open- and forest-grown balsam fir trees. In: Forest biomass studies: IUFRO working group on forest biomass studies, Young, H. (ed.). Univ. of Maine Coll. of Life Sci. and Agric., Orono, ME. pp 65-78.

Jenkins, J.C., Chojnacky, D. C., Heat, L.S. and Birdsey, R.A. 2003. Comprehensive database of diameter-based biomass regressions for North American tree species, Forest service, General Technical Report NE-319, 12 p.

Jose, S., Gillespie, A.R. and Pallardy, S.G. 2004. Interspecific interactions in temperate agroforestry, Agroforestry Systems 61:237-255.

Keyes, M.R. and Grier, C.C. 1981. Above- and belowground net production in 40-year-old Douglas fir stands on low and high productivity sites, Can. J. For. Res 11:599-605.

Kirby, K.R. and Potvin, C. 2007. Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project, For. Ecol. Management 246:208-221.

Kort, J. and Turnock, R. 1999. Carbon reservoir and biomass in Canadian prairie shelterbelts, Agroforestry Systems 44:175-189.

Kort, J. 1988. Benefits of windbreaks to field and forage crops, Agriculture Ecosystems and Environment 22/23:165-190.

Kumar, B.M. and Nair, P.K.R. (eds.). 2011. Carbon sequestration potential of agroforestry systems: Opportunities and Challenges. Springer, Dordrecht, the Netherlands, Advances in Agroforestry, 307 p.

Kutner, M.H., Nachtsheim, C.J. and Neter.J. 2004. Applied linear regression models, fourth ed., Irwin Inc., New York, USA, 701 p.

Lamlom, S.H. and Savidge, R.A. 2003. A reassessment of carbon content in wood: variation within and between 41 North American species, Biomass and Bioenergy 25:381-388.

Litton, C.M., Ryan, M.G. and Knight, D.H. 2004. Effects of tree density and stand age on carbon allocation patterns in post-fire lodge pole pine, Ecological Applications 14(2):460-475.

Loetsch, F., Zohrer, F. and Haller, K.E. 1973. Forest inventory, BLV Verlagsgesellschaft. Munchen, 469 p.

Lutz, J. 2011. How trees grow. http://www.forestresearchgroup.com/Newsletters/V8No2.pdf (7/1/2015).

McNab, W.H., Cleland, D.T., Freeouf, J.A., Keys Jr., J.E., Nowacki, G.J. and Carpenter, C.A (comps). 2005. Description of ecological sub regions: sections of the conterminous United States [CD-ROM], Washington, DC: U.S. Department of Agriculture, Forest Service, 80 p.

McHale, M.R., Burke, I.C., Lefsky, M.A, Peper, P.J. and McPherson, E.G. 2009. To use allometric relationships developed specifically for urban trees, Urban Ecosystems 12:95-113.

Miles, P.D. and Smith, W.D. 2009. Specific gravity and other properties of wood and bark for 156 tree species found in North America, USDA Forest Service Research Note NRS 38, 35p.

Montagnini, F. and Nair. P.K.R. 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems, Agroforestry Systems 61:281-295.

Nair, P.K.R. 2011. Carbon sequestration studies in agroforestry systems: a reality-check, Agroforestry Systems 86:243-253.

Nair, P.K.R., Nair, V.D. Kumar, B.M. and Haile, S.G. 2009. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal, Environmental Science and Policy 12(8):1099-1111.

Nakamura, T., Judd, K., Mess, M.I. and Small, M. 2005. A comparative study of information criteria for model selection. http://staffhome.ecm.uwa.edu.au/~00027830/pdf/IJBC16-2.pdf (7/1/2015)

Ogle, S.M., Adler, P.R., Breidt, F.J. et al. 2014. Quantifying greenhouse gas sources and sinks in cropland and grazing land systems. In quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity-scale inventory.. Office of the chief economist, U.S. Department of agriculture, Washington, DC. Tech. Bull. 1939, 606 p.

Oliver, W.W. and Rycker, R.A. 1990. Ponderosa pine. In: Silvics of North America: Conifers, Burns, Russell, M and Honkala, B.H. (Tech. Coords.), US Department of Agriculture, Forest Service, Washington DC, 2:877.

Parresol, B.R. 1999. Assessing tree and stand biomass: a review with examples and critical comparisons, Forest Science 45(4):573-593.

Picard, S.A.L. and Henry, M. 2012. Manual for building tree volume and biomass allometric equations: from field measurement to prediction, Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier, 215 p.

Prodan, M. 1968. Forest Biometrics, English ed. Pergamon Press, Oxford,UK, 447 p.

Raintree, J.B. 1986. An introduction to agroforestry diagnosis and designs, ICRAF, 55 p.

Rani, B.D., Kumar, K.R., Jose, S. and Pal, H.S. 2008. Ecological basis of agroforestry, CRC Press, Taylor & Francis Group, Boca Raton, FL, 382 p.

Rao, K.P.C., Verchot, V.L. and Laarman, J. 2007. Adaptation to climate change through sustainable management and development of agroforestry systems, ICRISAT 4:(1):30.

Schreuder, H.T. and Williams, M.S. 1998. Weighted linear regression using D^2H and D^2 as the independent variables, , Fort Collins, CO: U.S., Department of Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-6, 10 p.

Schoeneberger, M.M., Bentrup, G., de Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., Zhou, X. and Current, D. 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture, Journal of Soil and Water Conservation 67(5):128-136.

Schoeneberger, M.M. 2009. Agroforestry: working trees for sequestering carbon on agricultural lands, Agroforestry Systems 75:27-37.

Schumacher, F.X. and Hall, F.S. 1933. Logarithmic expression of timber-tree volume, Journal of Agriculture Research, 47:719-734.

Sharrow, S.H. and Ismail, S. 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA, Agroforest Syst 60:123-130.

Spears, S. 2000. Calculation of the mean annual increment by forest type and reconciling with expected management plan yields mean annual increment. http://www.fundymodelforest.net/pdfs/publications/management/Management_2000_Spears_%20Calculation%20of%20Mean%20Annual%20increment.pdf (7/1/2015).

Spurr, S.H. 1956. Forest associations of the Harvard Forest, Ecol. Monogr 26:245-262.

Stephenson, N.L., Das, A.J., Condit, R., et al. 2014. Rate of tree carbon accumulation increases continuously with tree size, Nature 507:90-101.

Udawatta, R.P. and Jose, S. 2011. Carbon sequestration potential of agroforestry practices in temperate North America. In: Carbon sequestration potential of agroforestry systems: opportunities and challenges, Kumar, B.M and Nair, P. K. R., Advances in Agroforestry, 1st Edition, 17:17-42.

USDA-FS (Forest Service) 2014. Ecoregions of the United States http://www.fs.fed.us/rm/ecoregions/products/map-ecoregions-united-states/ (7/1/2015).

USDA-FS (Forest Service) 2015. Forest Inventory and Analysis National Program: FIA Library. Database documentation. Washington, DC http://fia.fs.fed.us/library/database- documentation/ (7/8/2015).

USDA-FIA (Forest Inventory and Analysis) 2015. Data and tools: FIA DataMart, http://apps.fs.fed.us/fiadb-downloads/datamart.html (7/1/2015).

USDA-NRCS, (USDA Natural Resource Conservation Service) 2009. Conservation practice standard: windbreak/shelterbelt establishment (Feet) Code 380, http://efotg.sc.egov.usda.gov/references/public/MN/380mn.pdf (05/19/2015).

USDA-NRCS, (USDA Natural Resource Conservation Service) 2006. Land resource regions and major land resource areas of the United States, the Caribbean, and the Pacific basin, U.S. Department of Agriculture Handbook, 296 p.

USDA-NRCS, (USDA Natural Resource Conservation Service) 2015. Plants database, http://www.plants.usda.gov/java/ (7/1/2015).

Weiskittel, A.R., MacFarlane, D.W.; Radtke, P.J., Affleck, D.R., Temesgen, H., Woodall, C.W., Westfall, J.A. and Coulson, J.W. 2015. A call to compare methods for estimating tree biomass for regional and national assessments. http://www.ingentaconnect.com/content/saf/jof/pre-prints/content-jof14091 (7/1/2015).

Wells, O.O. 1964. Geographical variation in ponderosa pine. 1. The ecotypes and their distribution, Silvae Genetica 13:89-103.

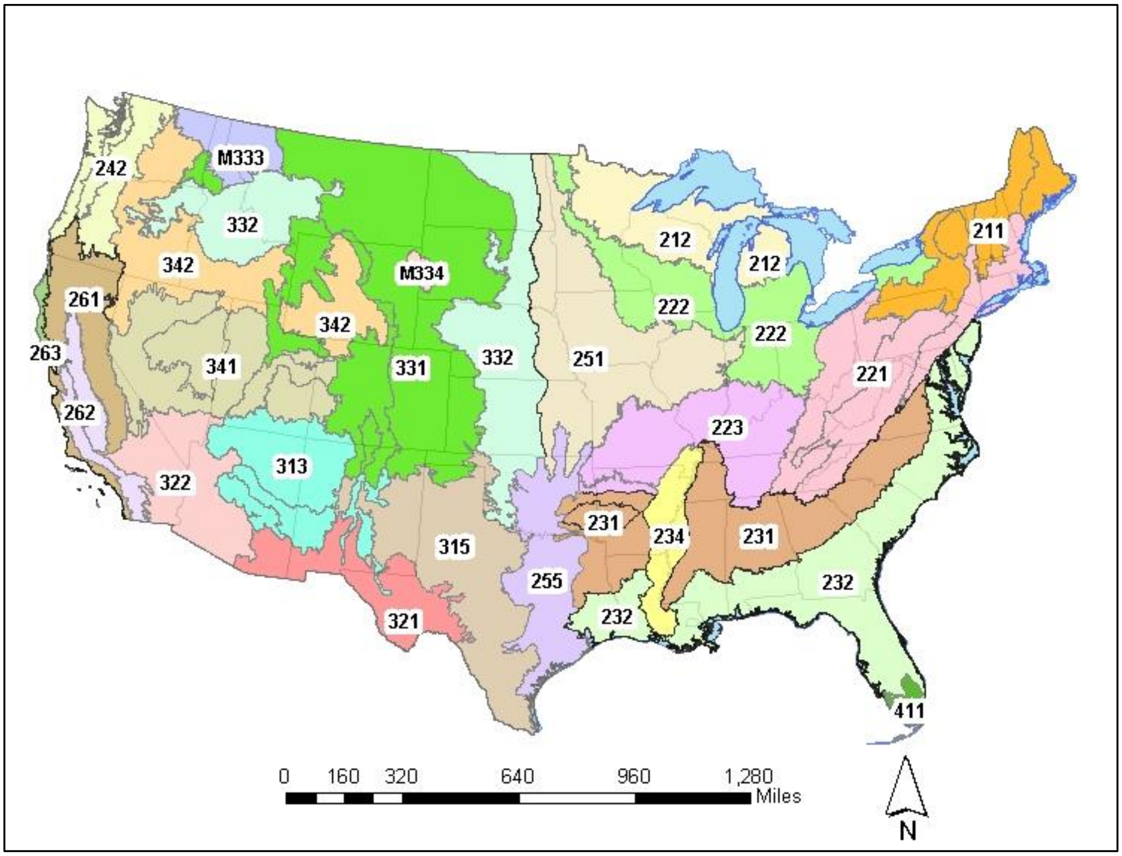
Woudenberg, S.W., Conkling, B.L., O'Connell, B.M., LaPoint, E.B., Turner, J.A. and Waddell, K.L. 2010. The Forest Inventory and Analysis Database: Database description and user's manual version 4.0 for Phase 2, http://www.fs.fed.us/rm/pubs/rmrs_gtr245.pdf (7/1/2015).

Xiao, C.W. and Ceulemans, R. 2004. Allometric relationships for below- and aboveground biomass of young Scots pines, Forest Ecology and Management 203:177-186.

Zhou, X., Schoeneberger, M.M., Brandle, R.J., Awada, T.N, Chu, J., Derrel, L.M., Li, J., Li, Y. and Mize, C.W. 2015. Analyzing the uncertainties in use of forest-derived biomass equations for open-grown trees in agricultural lands, Forest Science 15:144-161.

Zhou, X. and Hemstrom, M.A. 2009. Estimating aboveground tree biomass on forestland in the Pacific Northwest: a comparison of approaches, Res Pap PNW-RP-584, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 18 p.

Figure 3-1. Ecoregions of the United States.



Source: Bailey 1995 http://www.fs.fed.us/land/ecosysmgmt/index.html, http://www.eoearth.org/view/article/152244/) and McNab 2005.

Figure 3-2. Distribution of ecoregions within major regions in the United States.

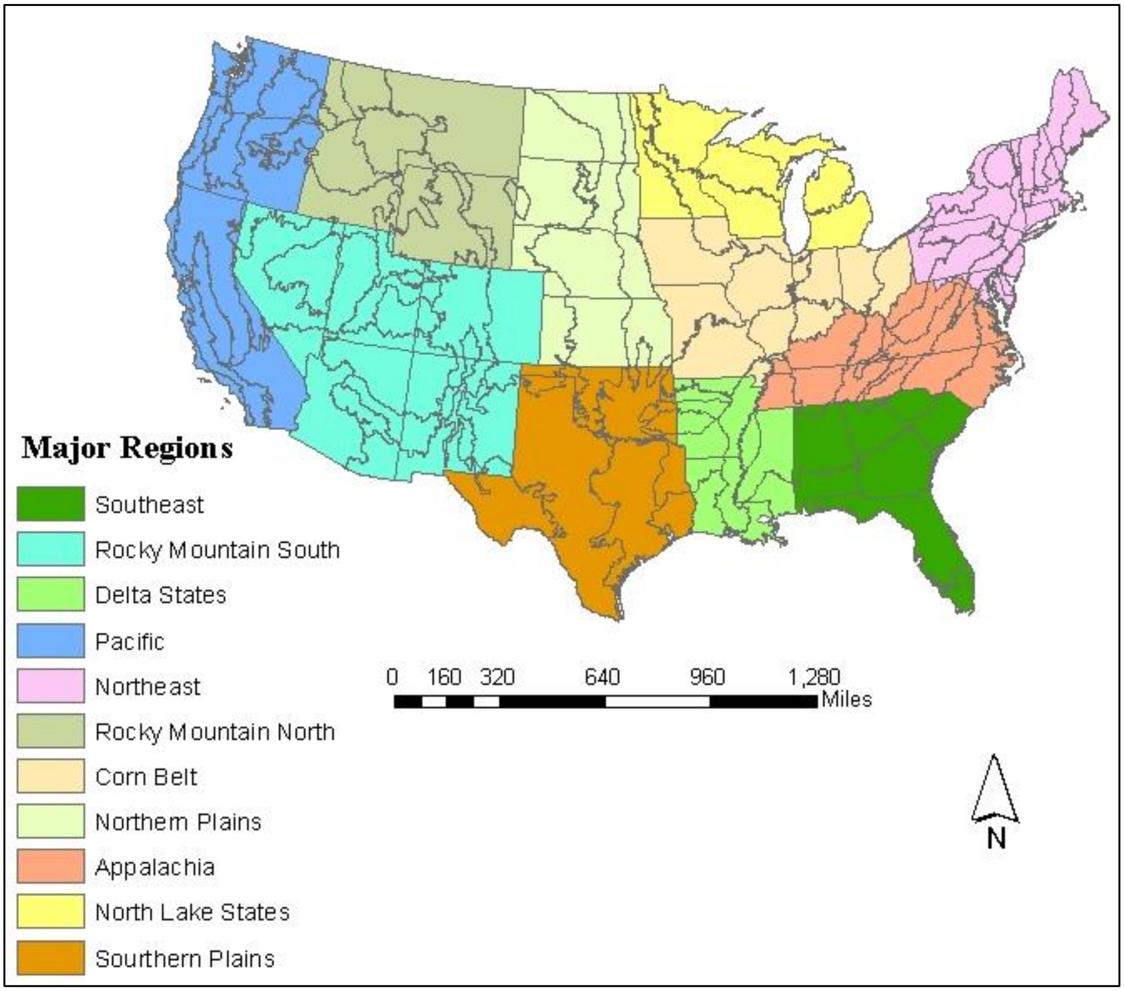


Figure 3-3. Allometric equations fitted from the relationships of total aboveground biomass (kg) against diameter at breast height (dbh in cm.) for *P. ponderosa*.

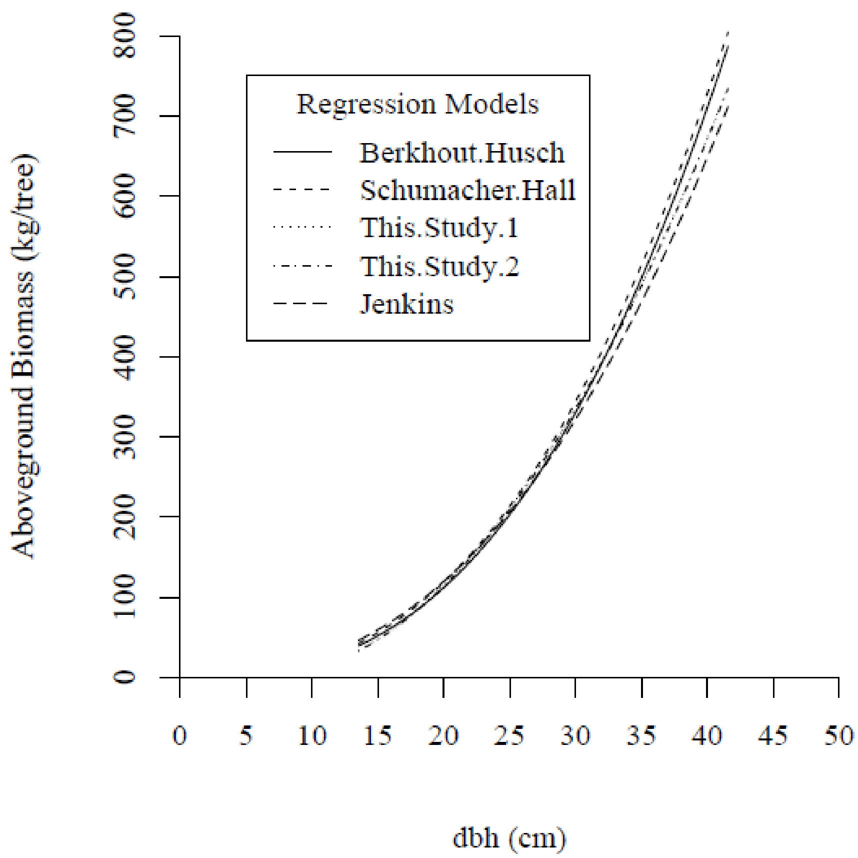


Table 3-1. Tree species with potential for windbreaks.

Tree species	Scientific name	FIA Code
Balsam fir	*Abies balsamea* (L.) Mill.	0012
Eastern red cedar	*Juniperus virginiana* L.	0068
Norway spruce	*Picea abies* (L.) Karsten	0091
Lodgepole pine	*Pinus contorta* Dougl. Ex Loud.	0108
Ponderosa pine	*Pinus ponderosa* Dougl. Ex Laws.	0122
Eastern white pine	*Pinus strobus* L.	0129
Scotch pine	*Pinus sylvestris* L.	0130
Loblolly pine	*Pinus taeda* L.	0131
Hackberry	*Celtis occidentalis* L.	0462
Green ash	*Fraxinus pennsylvanica* Marsh.	0544
Eastern cottonwood	*Populus deltoides* Bartr. Ex Marsh.	0742
American elm	*Ulmus americana* L.	0972
White oak	*Quercus alba* L.	0802
Bur oak	*Quercus macrocarpa* Michx.	0823
Northern red oak	*Quercus rubra* L.	0833
Southern red oak	*Quercus falcata* Michx.	0812

Source: FIA (2014) Nomenclature based on Harlow et al. (1991)

Table 3-2. Regression model forms to estimate aboveground tree biomass.

Author	Allometric equations
Berkhout *	$\text{bm} = \text{a} + \text{b}\ (\text{dbh})$
Spurr (1956)	$\text{bm} = \text{a} + \text{b}\ (\text{dbh})^2$
Spurr.mod (1956)	$\text{bm} = \text{a} + \text{b}\ (\text{dbh})^2 + \text{c}\ (\text{ht})$
Stoate*	$\text{bm} = \text{a} + \text{b}\ (\text{dbh})^2 + \text{c}\ (\text{dbh})^2\ \text{ht} + \text{d}\ (\text{ht})$
Hohenadl – Krenn*	$\text{bm} = \text{a} + \text{b}\ (\text{dbh}) + \text{c}\ (\text{dbh})^2$
Meyer(1953)	$\text{bm} = \text{a} + \text{b}\ (\text{dbh}) + \text{c}\ (\text{dbh})^2 + \text{d}\ (\text{dbh})\ \text{ht} + \text{e}\ (\text{ht})$
Kopezky*	$\text{bm} = \text{a} + \text{b}\ (\text{dbh})^2$
Naslund*	$\text{bm} = \text{a} + \text{b}\ (\text{dbh})^2 + \text{c}(\text{dbh})^2\text{ht} + \text{d}(\text{dbh})\text{ht}^2 + \text{e}\ (\text{dbh})^2$
Berkhout. Husch*	$\log(\text{bm}) = \log(\text{a}) + \text{b}\ (\log(\text{dbh}))$
Brenac*	$\log(\text{bm}) = \text{a} + \text{b}\ (\log(\text{dbh}) + \text{c}\ (1/\text{dbh})$
Schumacher-Hall (1933)	$\log(\text{bm}) = \log(\text{a}) + \text{b}\ (\log(\text{dbh}) + \text{c}\ (\log(\text{ht})$
Jenkins et al. (2003)	$\text{bm} = \text{e}^{(\text{a}+\text{b} \ln \text{dbh})}$

Source: Spurr (1956), Prodan et al 1968, * Loestch et al. 1973, bm = biomass, dbh= diameter at breast height (1.30 m), ht= total height (ft), a, b, c, d, e = regression coefficients, log = natural logarithm base e= 2.718282

Table 3-3. Goodness-of-fit statistics for the aboveground tree biomass equations.

Number	Author	Information Criteria					
		R sq.[1]	RSE	AIC	PRESS	VIF	FI
1	Berkhout	0.9086	66.50	206.9	105587.6	2.88	66.50
2	Spurr	0.9783	32.37	182.4	35252.5	1000.2	32.37
3	Spurr.mod	0.9293	58.47	202.26	82148.7	15.18	58.47
4	Stoate	0.977	33.36	182.82	38746.58	53.0	33.36
5	Hohenadl - Krenn	0.9698	38.21	186.95	33974.85	42.78	38.21
6	Meyer(1953)	0.9748	34.88	185.09	40955.98	362.96	34.88
7	Kopezky	0.9644	41.52	186.95	33974.9	1.0	41.52
8	Meyer mod.	0.9871	32.52	183.13	35711.2	1002.9	32.52
9	Naslud	0.9941	16.91	159.59	9361.2	6542.9	16.91
10	Berkhout and Husch	0.9371	0.2346	2.76	1.08	1.0	0.23
11	Brenac	0.9329	0.2422	4.76	1.23	41.58	1.18
12	Schumacher &Hall	0.9357	0.2372	4.0	1.26	2.83	1.16
13	This study.1[2]	0.9597	1.317	64.88	34.3	1.0	1.79
14	This study.2[3]	0.9571	1.359	66.84	45.33	2.88	1.85
15	Jenkins	0.987	0.2537	-	-	-	-

[1] R sq. = Adjusted R squared, RSE= Residual Standard Error, AIC= Akaike's Information Criteria, PRESS = Predicted Residual Sum of Squares and FI = Furnival Index.
[2] Local model based on dbh
[3] Local model based on dbh and height (ht)

Table 3-4. Coefficients and mean error in the estimates of the competing models after validation[1].

Number	Model	α^2	β	γ	R^2	Error (%)
10	Berkhout & Husch	-3.212	2.641	-	0.934	5.74
12	Schumacher &Hall	-3.221	2.851	-0.301	0.937	6.99
13	This study.1[3]	-4.363	0.754	-	0.960	3.46
14	This study.1[4]	-4.341	0.756	-0.009	0.957	3.10
15	Jenkins	-2.536	2.435		0.987	0.45

[1] 117 trees for training and 1 tree for testing; repeating 6 times for each model
[2] α, β and γ are regression coefficients, S.E = standard error
[3] Local model based on dbh
[4] Local model based on dbh and height (ht)

Table 3-5. Aboveground biomass estimates for *P. ponderosa* using the selected allometric equations projected to 50 years.

Model	Destructive sampling (kg tree^{-1})		FIA dataset (kg tree^{-1})	
	NE	MT	331	332
This Study 1	659.35±4.10	218.90±5.94	255.68±7.38	260.09±7.18
This Study 2	676.35±3.98	225.46±5.72	262.30±7.18	267.02±6.97
Jenkins 2003	661.17±1.30	221.13±0.82	256.23±0.56	260.45±0.59
Chojnacky 1[1]	667.73±1.24	223.74±0.78	259.71±0.52	264.04±0.56
Chojnacky 2[2]	863.74±0.99	262.65±0.60	308.26±.39	313.79±0.42

[1] Adjustment made to Jenkins equations by Chojnacky et al. (2014) considering pine trees with ≤ 0.40 (1) and ≥ 0.40 spg (2), where spg is specific gravity of wood of on green volume to dry-weight basis.
[2] Local model based on dbh
[3] Local model based on dbh and height (ht)

Table 3-6. Effect of the allometric equations on the estimates of the carbon storage potential (Mg tree^{-1}) for *P. deltoides* and *J. virginiana* projected to 50 years.

Region	*Populus deltoides*		*Juniperus virginiana*	
	Anurag (1989)[1]	Jenkins et al. (2003)	Jenkins et al. (2003)	Schell (1976)
North Lake States	0.12±0.05 (251)[2]	0.218±0.11 (251)	0.03±0.01 (251)	0.03±0.01 (251)
Corn Belt	0.19±0.04 (221)	0.39±0.12 (221)	0.21±0.01 (221)	0.26±0.01 (221)
Southern Plains	0.86±0.32 (255)	1.31±1.63 (255)	0.52±0.13 (255)	0.15±0.001 (255)
Delta States	0.29±0.10 (231)	0.72±0.34 (231)	0.06±0.001 (231)	0.08±0.001 (231)
Appalachia	0.32±0.14 (223)	0.85±0.50 (223)	0.03±0.006 (223)	0.04±0.008 (223)
North East	0.02±0.004 (222)	0.02±0.006 (222)	0.02±0.003 (222)	0.02±0.004 (222)
Northern Plains	0.06±0.02 (331)	0.08±0.04 (331)	0.073±0.02 (331)	0.09± 0.02 (331)

[1] Author and publication year of the allometric equation

[2] Tree mean biomass potential (Mg tree^{-1}) ± Standard Error and (Ecoregion)

Table 3-7. Average carbon storage potential estimates (Mg C ha^{-1} $year^{-1}$), for selected hardwood and conifer species, in the United States regions.

Region	Hardwoods		Conifers	
	Mean[1]	S.E.	Mean	S.E.
Northern Lake States	2.89[2]	0.40	2.42	0.23
Corn Belt	3.52	0.71	1.57	0.29
Southern Plains	13.60	7.72	3.84	0.04
Delta States	3.19	1.05	2.44	0.04
Appalachia	4.46	1.55	1.86	0.04
Rocky Mountain North	3.59	1.95	3.20	1.16
Rocky Mountain South	NA[3]	NA	NA	NA
Northeast	0.99	0.16	1.07	0.21
Northern Plains	2.88	0.35	3.18	1.32
Average	4.39	1.74	2.45	0.42

[1] Mean carbon storage potential for deciduous (816 trees) and conifer (1,111) tree species (USDA NRCS 2009) per ha per year during 50 years. Based on one row mono specie windbreak.

[2]. This number indicates that on average and based on all hardwood species considered this windbreak will store 2.89 Mg of C per hectare per year.

[3] Value underestimated in the FIA dataset (not considered for analysis)

NA= No available data.

CHAPTER 4: CARBON STORAGE POTENTIAL OF WINDBREAKS DESIGNS IN THE UNITED STATES

Abstract

The carbon storage potential for twelve field windbreak designs containing one-, two- and three-rows and nine farmstead windbreaks encompassing three- to ten-rows of mixed tree species were analyzed. Estimates of the carbon storage potential for eight coniferous and eight deciduous windbreak tree species were derived from the Forest Inventory and Analysis dataset. These values were the baseline to calculate the potential storage in the various windbreak designs, using a 50-yr growth period.

Carbon storage potentials for different field windbreak designs across regions ranged from 0.3 Mg C km^{-1} yr^{-1} for a single-row small-conifer windbreak in the Northeast region to 5.8 Mg C km^{-1} yr^{-1} for a three-row tall-deciduous windbreak in the Appalachia region. Carbon storage potentials for farmstead windbreaks ranged from 0.8 Mg C 300 m^{-1} yr^{-1} for a three-row of mixed tree species windbreak in the Rocky Mountain North to 12.7 Mg C 300^{-1} yr^{-1} for a ten-row of mixed tree species windbreak in Delta States region. Our study indicates these planting designs have the potential to store large amounts of carbon in the woody biomass above- and belowground.

Key words: Agroforestry systems, shelterbelts, biomass, windbreak designs, carbon storage.

Introduction

Windbreaks are an effective management activity for reducing soil erosion, providing crop/livestock/road/building protection, providing wildlife habitat, enhancing landscape aesthetics, and mitigating odor, dust, and pesticide drift from agricultural operations, as well as many other services (Brandle et al. 2009, Tyndall and Colletti 2007). Additionally, they are being regarded as an effective strategy for sequestering more carbon in United States agricultural lands (CAST 2011). Despite the capacity of windbreaks to sequester C in agricultural operations while providing many other valued co-benefits, little work has been done to document this potential in the United States and many questions remain.

Updated, standardized and representative statistics on carbon storage and emissions reductions are not available for this agroforestry practice (Udawatta and Jose 2011, Nair 2011, Schoeneberger et al. 2012). Although the limited literature indicates net gains in carbon sequestration by windbreaks, lack of rigorous data on the area under this practice (Dixon 1995, Nair 2010, Schoeneberger et al. 2012), consistent experimental procedures, and data-gathering protocols (Udawatta and Jose 2011, Nair 2011) make these data very difficult to compare and generalize.

Carbon storage potential for windbreaks has been derived from current forest inventory, stand-based equations and sometimes limited field data (Udawatta and Jose 2011). Final results have been based on different methods and procedures making estimations vary widely. Several methodological challenges face researchers interested in making comparisons among and aggregating these estimates.

Despite the limited data, some estimates for the carbon storage potentials of U.S. windbreaks, using different approaches, have been reported. Unfortunately, these estimates were based on different biomass calculations, geographic location, and windbreak arrangement and conditions. Nair and Nair (2003) projected 85 million ha under windbreaks and sequestration potential of 4 Tg C per year. Based on estimate of 94 million ha of cropland in the North Central region, Brandle et al. (1992) reported a potential of 215, 13 and 0.18 Tg C during 20 years by windbreaks for protection of crops, farmsteads and roads, respectively. Such approaches create disparity in the estimates; greatly limiting their use and demonstrating the need standardized experimental procedures and data gathering protocols (Nair 2011, Udawatta and Jose 2011)

Evaluating the carbon storage potential for standardized windbreak designs can provide the basis to generate accurate information for this agroforestry system in different scenarios and in different regions. The purpose of this study was to evaluate the carbon storage potential for different windbreak designs in nine regions of the continental United States.

Materials and Methods

Our study was confined to field and farmstead windbreak systems. To design these windbreak structures we used the tree spacing defined in the practice standards for windbreaks under code 380 (USDA-NRCS 2009). Field windbreak designs contained from one-row to three-rows of the deciduous and conifer trees (Tables 4-1 and 4-2). Farmstead windbreak designs varied from a minimum of three-rows for southern regions to a maximum of ten-rows for northern regions (Table 4-3) with a mixture of species.

From these designs, above and belowground carbon storage potential values were calculated.

Prior work evaluated several allometric models for suitability in the prediction of biomass in species of windbreak trees (See Chapter 3). Sixteen tree species (eight hardwoods and eight conifers) were selected based of their potential for use in windbreaks. The average carbon storage potential for these windbreaks growing in nine regions of the United States was then calculated. Because windbreaks are linear landscape features, density is usually expressed in terms of the number of trees per unit length (see Kort 1998). As carbon storage potentials for management activities are generally reported on an area basis, we converted windbreak length to an area basis by factoring in the width of the windbreak. The width will vary with design (tree species and spacing) and with time as the trees grow.

Windbreak Designs

While each windbreak planting is ultimately the product of the farmer's decision regarding its design, we selected twelve representative field windbreak designs containing one-, two- or three-rows and nine farmstead windbreaks containing three- to ten-rows and were evaluated. See details in Tables 4-1, 4-2 and 4-3.

The area occupied by a windbreak was calculated according to the tree canopy spread area at age 20 years (Table 4-1) and the width of the equipment used to maintain the windbreak (20 ft. or 6.0 m). The calculations were made using two approaches. A length-based approach (Figure 4-1a): which was reported in kilometers and miles and defined as the amount of carbon stored per unit length; and area-based approach (Figure

4-1b) which was defined as the sum of the area occupied by the windbreak and reported on a per unit (ha) basis.

A single row windbreak may start out with a minimum width between 8 and 10 ft., but may also just as often be as narrow as 4 ft. A multiple row windbreak will have an additional space between rows. Given this information standard designs for one row, two row and three row windbreaks were developed. Windbreak designs were accomplished according to the conservation practice standards for windbreaks /shelterbelts establishment under USDA-NRCS code 380 (USDA-NRCS 2009).

For example, a 100 m length windbreak with a 10 m width would occupy a strip of 1,000 m^2. Our field windbreak designs were based on having a maximum of 5% of the cropping area occupied which has generally been found to provide a positive net return on the field windbreak investment.

Carbon Storage Potential of Windbreak Designs in Different Regions

The average carbon storage potential for hardwoods and conifers, estimated for different regions (Table 3-5), was used as the baseline values for calculating the C potential of the windbreak designs. Because *Juniperus virginiana* is classified as small conifer tree (USDA-NRCS, 2009), it was analyzed separately. Likewise, values for carbon storage by shrubs were also analyzed separately and used data from Zhou et al. (2007). They estimated that above-ground woody biomass value of a one-row, 2-m-spacing Russian-olive (*Elaeagnus angustifolia* L.) tree shelterbelt with different survival rates, at age of 50 years, was between 7.8 and 8.7 metric tons per 100-m length (3.3±0.18 kg C yr^{-1} $tree^{-1}$).

Results

Carbon Storage Potential for Different Windbreak Designs

Carbon storage potential for windbreak designs depended on tree spacing and tree species performance. Carbon storage potential for the designed field windbreaks across all studied regions, on a length basis, is given in Table 4-4. For field windbreaks, mean carbon storage potential (based on 50-years growth) ranged from 0.65±0.11 Mg C km^{-1} yr^{-1} for a single-row small-conifer windbreak to 4.14±1.64 Mg C km^{-1} yr^{-1} for a three-row tall-conifer. Carbon storage potential for farmstead windbreaks, again based on 50-years growth, ranged from 2.29±0.37 Mg C km^{-1} yr^{-1}, for a three-row of mixed tree species to 12.69±3.10 Mg C km^{-1} yr^{-1} for ten-row of mixed tree species (Table 4-5).

Regional carbon storage potentials for the windbreak designs with suitable species are displayed in Tables 4-6 and 4-7. For field windbreaks the carbon storage of the windbreak, based on 50-years growth, ranged from a low of 0.5 Mg ha^{-1} yr^{-1} for a one-row tall conifer in North East region to a high of 7.7 Mg $ha^{-1}yr^{-1}$ for one-row-small-conifer in the Corn Belt region (Table 4-6). As seen in Table 4.6, one row windbreak planting in the different designs had the highest C storage potential because in these designs alley width is not considered (see table 4.1).

Carbon storage potential for the different farmstead windbreak designs ranged from 0.8 for an one-row small conifer and two-rows tall conifers in Rocky Mountain North to 12.7 Mg C ha^{-1} yr^{-1} for a 10 ten-row of mixed tree species in the Delta States (Table 4-7).

Discussion

The values calculated in this study indicate that typically used field and farmstead windbreak designs have the potential to sequester large amounts of carbon in the woody biomass in various regions of the United States, further supporting its promotion as an added agricultural strategy for increasing C storage capacity. The amount of carbon stored in these systems will be heavily influenced by the design, tree species and ultimate health of the windbreaks over time. Many field and farmstead windbreak designs are possible in the United States agricultural lands. The final practice design for each planting will be a reflection of land availability, economics and farmer goals (Brandle et al. 1988, Tamang et al. 2015).

The carbon storage potential for windbreak designs in different regions varied significantly. The growth performance reported on FIA database for the different tree species affected the final results. Net carbon storage in Rocky Mountains South was underestimated when compared to the reports in the literature. It is known that Ponderosa pine (*Pinus ponderosa* Dougl. ex-Laws) is a wide-ranging conifer occurring throughout the western United States, southern Canada and northern Mexico (Linhart 1988, Burns and Honkala 1990) with the greatest growth range of any commercial timber species in America (Oliver and Russell 1990). The carbon storage potential calculated in this study was very low under the conditions found in the Rocky Mountains South region (Table 4-6). This may have been due to the lack of accurate data in the FIA dataset. Regardless, given the need for windbreaks in regions where ponderosa pine is one of the better species to use, our estimates found windbreak carbon storage potentials to range from an average of 3.58 to 4.2 to Mg C ha^{-1} yr^{-1} for farmstead and field windbreaks, respectively, in this region.

As reported in our prior study (Chapter 3), these outcomes reflect the effects of growth, locations and data set concerns. The carbon potential calculated for hardwood, conifers, small conifers and shrubs in the different designs was considerable. The results from this study demonstrate the importance of species selection and standardized protocols in enhancing our estimates of the amount carbon stored by windbreaks and reducing uncertainty of these estimates (Tables 4-4 to 4-7). If researchers report storage estimates together with protocols used and tree ages, these uncertainties can be reduced. For example, Kort and Turnock (1999) reported that hybrid poplar (*Populus deltoides* x *Populus nigra* Bartr. Ex. Marsh) sequestered 544 kg C $tree^{-1}$ during 33 years and green ash (*Fraxinus pennsilvanica* Marsh) 162 kg C $tree^{-1}$ during 53 years in above- and belowground. Such information facilitates use and accuracy of interpretation of the reported data in carbon storage estimation excercises.

Properly designed windbreaks with the right tree in the right place undoubtedly can provide considerable carbon storage. An important aspect in the general consideration of field windbreak use is the amount of land taken out from production. According to Brandle et al (1992), field windbreaks should occupy less than 5% of the agricultural lands to be economically viable based on production differences. Windbreak designs containing three rows stored more carbon than single row planting but exceeded this 5% threshold. There are tradeoffs between crop productive and carbon storage services which must be considered by the landowner when designing windbreaks. However, as windbreaks have been shown to provide many other economic benefits and social goods (Kulshreshtha and Kort 2009), such as C sequestration, future markets and other incentives, may shift this 5% threshold. Different windbreak designs are possible to store and reduce carbon emissions from farm operations in the United States. The wise combination of these windbreak designs and the proper selection of tree species in each region are key factors to better exploit their C storage potential, along with the other services they can provide.

Conclusions

We constructed a standardized approach for evaluating C storage in the woody biomass of field and farmstead windbreaks. This approach allowed us to estimate potentials for this practice looking at such variables as tree species, windbreak design and regional location. Values obtained provide us with a basis for evaluating the potential C contributions of these systems within farm operations in the United States. Results from this study indicate that field and farmstead windbreaks can be an effective tool to offset the negative effects of the agricultural systems in the global carbon budget. The structure of a windbreak will depend on the purpose, the expected benefits and the site characteristics, and will in turn determine the carbon storage potential these systems can provide. The findings from this study will add to the ability of decision makers to evaluate tradeoffs involved when making management decision on agricultural lands in the United States.

References

Brandle, J.R., Hodges, L., Tyndall, J. and Sudmeyer, R.A. 2009. Windbreak practices. In: Garrett HE (ed.) North American Agroforestry, an integrated science and practice, 2nd American Society of Agronomy, Madison, pp 75-104.

Brandle, J.R., Hintz, D.L. and Sturrock, J.W. 1988. Windbreak Technology, Elsevier Science Publishers, Amsterdam, 598 p.

Brandle, J.R., Wardle, T.D. and Bratton, G.F. 1992. Opportunities to increase tree plantings in shelterbelts and their potential impacts on carbon storage and conservation, Forests and Global Change, Edited by R.N. Sampson and D. Hair. American Forests, Washington DC, pp. 157-175.

Brunsdon, C., Fotheringham, A.S. and Charlton, M. 1996. Geographically weighted regression: a method for exploring spatial non-stationarity, Geographical Analysis 28(4):281-298.

Burns, Russell, M. and Honkala, B.H. (Tech. Coords.) 1990. Silvics of North America Agriculture Handbook 654.U.S. Department of Agriculture, Forest Service, Washington DC, 2:877.

CAST, (Council for Agricultural Science and Technology) 2011. Carbon sequestration and greenhouse gas fluxes in agriculture: Challenges and opportunities, Task Force Report, No. 142, 106 p.

Dixon, R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gases? Agroforestry Systems 31:99-116.

Kort, J. 1998. Benefits of windbreaks to field and forage crops, Agriculture Ecosystems and Environment 22/23:165-190.

Kort, J. and Turnock, R. 1999. Carbon reservoir and biomass in Canadian prairie shelterbelts, Agroforestry Systems 44:175-189.

Kulshreshtha, S. and Kort, J. 2009. External economic benefits and social goods from prairie shelterbelts, Agroforestry Systems 75:39-47.

Linhart, B. 1988. Ecological and evolutionary studies of ponderosa pine in the Rocky Mountains. In: The species and its management: Baumgartner, D.M. and Lotan, J.E. (compilers), Symposium proceedings; Spokane and Pullman, WA, Washington State University, Cooperative Extension, pp 77-89.

Nair, P.K.R. and Nair, V.D. 2003. Carbon Storage in North American agroforestry systems, , In: The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect, Kimble, J., Heath, L.S. Birdsey, R.A. and Lal. R. (eds.), Boca Raton, FL: CRC Press LLC, pp 333-346.

Nair, P.K.R, Nair, V.D. and Kumar B.M. 2010. Carbon sequestration in agroforestry systems, Adv. Agronomy 108:237-307.

Oliver, W.W. and Russell A.R. 1990. Ponderosa Pine (*Pinus ponderosa* Dougl. ex Laws.) in: Burns, Russell M., and Barbara H. Honkala, tech. coords. 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654. http://www.na.fs.fed.us/spfo/pubs/silvics_manual/table_of_contents.htm (7/8/2015).

Schoeneberger, M.M., Bentrup, G., de Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., Zhou, X. and Current, D. 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture, Journal of Soil and Water Conservation 67(5):128-136.

Tamang, B. Andreou, G.M., Friedman, H.M. and Rockwood, D.L. 2015. Windbreak designs and planting for Florida agricultural fields. http://edis.ifas.ufl.edu/fr289 (7/8/2015).

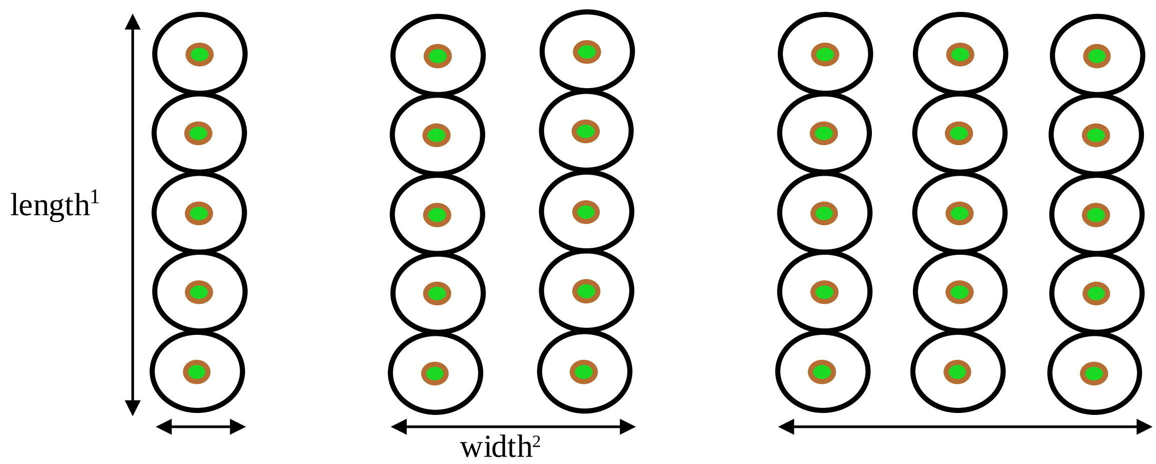
Tyndall, J. and Colletti, J. 2007. Mitigating swine odor with strategically designed shelterbelt systems: a review, Agroforest Systems 69:45-65.

Udawatta, R.P. and Jose, S. 2011. Carbon sequestration potential of agroforestry practices in temperate North America. In: Carbon sequestration potential of agroforestry systems: opportunities and challenges, Kumar, B. Mohan; Nair, P.K.R. (eds.), Advances in Agroforestry, 1st ed., 17:17-42.

USDA Natural Resource Conservation Service (USDA-NRCS) 2009. Conservation practice standard: windbreak/shelterbelt establishment (Feet) Code 380, http://efotg.sc.egov.usda.gov/references/public/MN/380mn.pdf (7/8/2015).

Zhou, X., Brandle, R.J., Schoeneberger, M.M. and Awada, T.N. 2007. Developing above-ground woody biomass equations for open-grown, multiple-stemmed tree species: Shelterbelt-grown Russian-olive, Forest Ecological Modelling 202:311-323.

Figure 4-1. Windbreak length and area approaches for reporting C storage potentials in windbreaks.



[1] Length approach: trees density for length of the windbreak, resulting in C stored by kilometer of windbreak
[2] Area approach: tree density per unit of area including the alley, resulting in C stored per area occupied by a windbreak design. For our study, alleys between rows were set at 6.0 meters width as cited by USDA-NRCS (2009).

Table 4-1. Tree distribution and amount per hectare (Area-based approach) in different field windbreak designs.

Field windbreak design	Rows	Tree spacing (m)		Number of trees per hectare			
		Within	Between	Sh[1]	Scon	Tdc	Tcon
One row small shrub	1	1.2	-	6,831	-	-	-
One row small coniferous	1	2.0	-	-	2,525	-	-
One row tall deciduous	1	3.5	-	-	-	-	814
One row tall coniferous	1	3.0	-	-	-	1,111	-
Two rows tall deciduous	2	3.5	6.0[2]	-	-	-	474
Two rows tall coniferous	2	3.0	6.0	-	-	553	-
One row tall coniferous and one row tall deciduous	2	3.5x3.0	6.0	-	-	269	234
One row tall coniferous and one row shrubs	2	3.0x1.2	6.0	672	-	269	-
One row tall deciduous and one row shrubs	2	3.5x1.2	6.0	672	-	-	234
One row tall coniferous and one row small conifer	2	3.0x2.0	6.0	-	827	269	-
One row tall deciduous and one row small conifer	2	3.5x2.0	6.0	-	827	-	234
Three rows tall coniferous	3	3.0x3.0x3.0	6.0	-	-	553	
Three row tall deciduous	3	3.5x3.5x3.5	6.0	-	-	-	474
Two rows tall deciduous and one row tall coniferous	3	3.0x3.0x3.5	6.0	-	-	179	312
One row tall deciduous, one row tall conifers and one row shrubs	3	3.5x3.0x1.2	6.0	448	-	179	156
One row tall deciduous, one row tall coniferous and one row small coniferous	3	3.5x3.0x2.0	6.0	-	276	179	156

[1] Sh= Shrubs, Scon= Small coniferous, Tdc = Tall deciduous, Tcon= Tall coniferous.

[2] For this study, an equipment alley of 6 m width was selected (USDA-NRCS 2009)

Table 4-2. Number of trees in different field windbreak designs using the length-based approach designs according to NRCS recommendations (USDA-NRCS 2009).

Field windbreak design	Number of trees per kilometer			
	Sh[1]	Scon	Tdc	Tcon
One row small shrub	820	-	-	-
One row small coniferous	-	505	-	-
One row tall deciduous	-	-	285	-
One row tall coniferous	-	-		328
Two rows tall deciduous	-	-	570[2]	-
Two rows tall coniferous	-	-	-	656
One row tall coniferous and one row tall deciduous	-	-	285	328
One row tall coniferous and one row shrubs	820	-	-	328
One row tall deciduous and one row shrubs	820	-	285	-
One row tall deciduous and one row small deciduous	-	505	-	328
One row tall deciduous and one row small coniferous	-	505	285	-
Three rows tall coniferous	-	-	-	984
Three row tall deciduous	-	-	855	-
Two rows tall deciduous and one row tall coniferous	-	-	570	328
One row tall deciduous, one row tall coniferous and one row shrubs	820	-	285	328
One row tall deciduous, one row tall coniferous and one row small coniferous	-	505	285	328

[1] Sh= Shrubs, Scon= Small coniferous, Tdc = Tall deciduous, Tcon= Tall coniferous

[2] Two- and three- rows spacing included an equipment alley of 6 m between rows (USDA-NRCS 2009)

Table 4-3. Number of trees in different farmstead windbreak designs based on NRCS recommendations (USDA-NRCS 2009).

Farmstead windbreak designs	Number of trees in 300 m windbreak			
	Sh[1]	Scon	Tdc	Tcon
One row shrubs and two rows tall conifers	246[2]	-	-	198
One row small conifer and two rows tall conifers	-	150	-	198
One row small conifer, one rows tall conifers, one row deciduous and shrubs	246	150	87	99
Two rows tall conifers, two rows tall deciduous and shrubs	246	-	174	198
Two rows tall conifers, one rows tall deciduous and two rows shrubs	492	-	87	198
Two rows tall conifers, two rows tall deciduous and two rows shrubs	492	-	174	198
Two rows tall conifers, one row small conifer, two rows tall deciduous and two rows shrubs	492	150	174	198
Three rows tall conifers, three rows tall deciduous and two rows shrubs	492	-	261	297
Three rows tall conifers, five rows tall deciduous and two rows shrubs	492	-	435	297

[1] Sh= Shrubs, Scon= Small coniferous, Tdc = Tall deciduous, Tcon= Tall coniferous
[2] Two- and three- rows spacing included an equipment alley of 6 m width between rows (USDA-NRCS 2009)

Table 4-4. Total (above- and belowground woody biomass) mean potential carbon stored for field windbreak designs based on windbreak length.

Field windbreak design	Rows	Carbon storage potential (Mg C km^{-1} yr^{-1}) in the regions of the United States[1]								
		NLS[2]	CB	SP	DS	AP	RMN	RMS	NE	NP
One row small coniferous	1	0.7	1.6	1.5	1.5	1.1	0.8	0.8	0.4	1.2
One row tall deciduous	1	1.0	0.6	1.0	1.0	1.6	0.5	-	0.3	0.7
One row tall coniferous		0.7	0.9	1.1	1.2	1.2	0.7	-	0.3	1.1
Two rows tall deciduous	2	2.0	1.3	2.1	2.0	3.1	1.0	-	0.7	1.4
Two rows tall coniferous	2	1.4	1.7	2.3	2.5	2.3	1.4	-	0.6	2.2
One row tall coniferous and one row tall deciduous	2	1.7	1.5	2.2	2.2	2.7	1.2	-	0.7	1.8
One row tall coniferous and one row small conifer	2	1.4	2.4	2.6	2.7	2.3	1.5	0.8	0.7	2.3
One row tall deciduous and one row small conifer	2	1.7	2.2	2.5	2.5	2.7	1.3	0.8	0.7	1.9
Three rows tall coniferous	3	2.1	2.6	3.4	3.7	3.5	2.1	-	1.0	3.3
Three row tall deciduous	3	3.0	1.9	3.1	3.0	4.7	1.5	-	1.0	2.1
Two rows tall deciduous and one row tall coniferous	3	3.8	2.8	4.3	4.2	5.8	2.2	-	1.4	3.2
One row tall deciduous, tall conifers and small conifer	3	2.4	3.1	3.7	3.7	3.8	2.0	0.8	1.1	3.0

[1] Tree survival rate of 90 percent was assumed. Replanting will be needed if survival rate decreases in the 2nd or 3rd year.

Table 4-5. Total (above- and belowground woody biomass) mean carbon stored for farmstead windbreak designs based on length of windbreak.

Farmstead windbreaks designs	Rows	Carbon storage potential Mg C 300 m^{-1} yr^{-1}								
		NLS	NP	CB	SP	DS	AP	RMN	RMS	NE
One row shrubs and two rows tall conifers	3	2.5	2.8	3.3	3.5	3.3	2.5	1.2	1.8	3.2
One row small conifer and two rows tall conifers	3	1.9	3.0	3.4	3.6	3.1	2.0	0.8	0.9	3.1
One row small conifer, one rows tall conifers, one row deciduous and shrubs	4	3.4	4.0	4.5	4.6	4.7	3.0	2.0	2.2	4.0
Two rows tall conifers, two rows tall deciduous and shrubs	5	4.4	4.0	5.2	5.3	6.2	3.4	1.2	2.4	4.5
Two rows tall conifers, one rows tall deciduous and two rows shrubs	5	4.7	4.6	5.4	5.6	5.9	4.1	2.4	3.3	5.1
Two rows tall conifers, two rows tall deciduous and two rows shrubs	6	5.6	5.2	6.4	6.5	7.4	4.6	2.4	3.6	5.7
Two rows tall conifers, one row small conifer, two rows tall deciduous and two rows shrubs	7	6.2	6.6	7.7	7.8	8.4	5.3	3.2	4.0	6.8
Three rows tall conifers, three rows tall deciduous and two rows shrubs	8	7.2	6.6	8.4	8.5	9.8	5.7	2.4	4.3	7.4
Three rows tall conifers, five rows tall deciduous and two rows shrubs	10	9.0	7.8	10.3	10.3	12.7	6.6	2.4	4.9	8.6

[1]Tree survival rate of 90 percent was assumed. Replanting will be needed if survival rate decreases in the 2^{nd} or 3^{rd} year.

Table 4-6. Regional carbon storage potential for field windbreak designs in some regions of the United States.

Field windbreak design	Rows	Carbon storage potential (Mg C ha^{-1} yr^{-1}) in the regions of the United States[1]								
		NLS[2]	CB	SP	DS	AP	RMN	RMS	NE	NP
One row small coniferous	1	3.5[3]	7.7	7.4	7.3	5.5	4.2	4.2	1.9	6.1
One row tall deciduous	1	2.9	1.9	3.0	2.8	4.5	1.4	-	1.0	2.0
One row tall coniferous	1	2.4	2.9	3.8	4.2	3.9	2.3	-	1.1	3.8
Two rows tall deciduous	2	1.7[4]	1.1	1.7	1.6	2.6	0.8	-	0.6	1.1
Two rows tall coniferous	2	1.2	1.4	1.9	2.0	1.9	1.1	-	0.5	1.8
One row tall coniferous and one row tall deciduous	2	1.4	1.2	1.8	1.8	2.2	1.0	-	0.6	1.5
One row tall coniferous and one row small conifer	2	1.8	3.3	3.4	3.4	2.8	1.9	1.4	0.9	2.9
One row tall deciduous and one row small conifer	2	2.0	3.1	3.3	3.2	3.1	1.8	1.4	0.9	2.6
Three rows tall coniferous	3	1.2	1.4	1.9	2.0	1.9	1.1	-	0.7	1.8
Three row tall deciduous	3	1.7	1.1	1.7	1.6	2.6	0.8	-	0.6	1.1
Two rows tall deciduous and one row tall coniferous	3	1.5	1.2	1.8	1.8	2.3	0.9	-	0.6	1.4
One row tall deciduous, tall conifers and small conifer	3	1.3	1.7	2.0	2.0	2.1	1.1	0.6	0.6	1.7

[1] Biomass stored based on the area-based approach. For information about spacing see Table 4.1.
[2] [1]NLS = Northern Lake States, CB = Corn Belt, SP = Southern Plains, DS = Delta States, AP = Appalachia, RMN = Rocky Mountains North, RMS= Rocky Mountains South, NE = North East, NP = Northern Plains
[3]Tree survival rate of 90 percent was assumed. Replanting will be needed if survival rate decreases in the 2nd or 3rd year.

Table 4-7. Regional carbon storage potential of different farmstead windbreak designs in some regions of the United States.

Farmstead Windbreaks	Rows	Carbon storage potential (Mg C ha^{-1} yr^{-1}) in the regions of the United Stattes[1]								
		NLS[2]	CB	SP	DS	AP	RMN	RMS	NE	NP
One row shrubs and two rows tall conifers	3	0.84[3]	0.93	1.09	1.16	1.10	0.82	0.41	0.60	1.08
One row small conifer and two rows tall conifers	3	0.64	0.99	1.13	1.19	1.02	0.67	0.25	0.31	1.04
One row small conifer, one rows tall conifers, one row deciduous and shrubs	4	1.14	1.33	1.51	1.52	1.56	1.01	0.66	0.72	1.32
Two rows tall conifers, two rows tall deciduous and shrubs	5	1.45	1.32	1.73	1.76	2.05	1.12	0.41	0.81	1.50
Two rows tall conifers, one rows tall deciduous and two rows shrubs	5	1.55	1.53	1.82	1.86	1.98	1.38	0.81	1.11	1.69
Two rows tall conifers, two rows tall deciduous and two rows shrubs	6	1.86	1.73	2.13	2.16	2.46	1.53	0.81	1.22	1.91
Two rows tall conifers, one row small conifer, two rows tall deciduous and two rows shrubs	7	2.07	2.19	2.58	2.60	2.79	1.78	1.06	1.33	2.27
Three rows tall conifers, three rows tall deciduous and two rows shrubs	8	2.38	2.19	2.80	2.84	3.28	1.88	0.81	1.42	2.45
Three rows tall conifers, five rows tall deciduous and two rows shrubs	10	3.00	2.58	3.43	3.43	4.23	2.18	0.81	1.63	2.88

[1] Biomass stored based on the area-based approach. For information about spacing see Table 4.1.
[2] [1]NLS = Northern Lake States, CB = Corn Belt, SP = Southern Plains, DS = Delta States, AP = Appalachia, RMN = Rocky Mountains North, RMS= Rocky Mountains South, NE = North East, NP = Northern Plains
[3]Tree survival rate of 90 percent was assumed. Replanting will be needed if survival rate decreases in the 2nd or 3rd year.

CHAPTER 5: POTENTIAL OF WINDBREAKS TO REDUCE CARBON EMISSIONS BY AGRICULTURAL OPERATIONS

Abstract

Along with sequestering C, windbreaks on farms are able to contribute to greenhouse mitigation through emission avoidance mechanisms. To evaluate the magnitude of these contributions, emission avoidance contributions for field and farmstead windbreak designs in regions across the United States were estimated, along with greenhouse gas emission budgets for corn, soybean, winter wheat and potato operations. Carbon equivalent (CE) emission numbers from different energy sources used for farming and consumed by farmsteads were taken from the literature to calculate the CE emissions at the farm level and the expected variation of these emissions due to cropping systems and region. We looked at farming scenarios with large (600 ha), mid (300 ha) and small-size (60 ha) farms, containing farmsteads built before and after 2000, and growing different cropping systems. Based on practice objectives and information in the literature, windbreak scenarios were assumed to be up to 5% of the crop area for field windbreaks. Emission avoidance for farmstead windbreaks were assumed to provide a 10 and 25% reduction in energy usage for space conditioning and heating, respectively.

Carbon equivalent (CE) emissions were found to range from a low of 0.15 Mg CE ha^{-1} for non-irrigated soybean systems to a high of 1.3 Mg CE ha^{-1} for irrigated potato systems. CE emissions for heating and cooling farmsteads ranged from 1.4 to 2.5 Mg CE house^{-1}. Total reduction of CE emissions by windbreaks on farm systems ranged from a

low of 0.8 Mg CE yr^{-1} for a 60-ha farm with a home built before 2000 to 39.1 Mg CE yr^{-1} for a 600-ha farm with a home built after 2000. Avoided CE emissions from fewer acres farmed and less energy used for heating and cooling the farmstead make windbreaks a promising strategy for reducing GHG emissions from agriculture in the United States.

Key words: carbon storage, reduced carbon emissions, crop emissions, farm scenarios.

Introduction

Reduction of greenhouse gas (GHG) emissions is at the core of the current worldwide discussion on climate change mitigation. Along with direct C storage, there are numerous emission reduction approaches being considered (IPCC 2013). One such approach is a change in consumptive behavior coupled with a reduction in the use of fossil fuels which results in avoided GHG emissions. In the agricultural sector, agroforestry practices offer a number of management practices which could result in avoided GHG emissions (Schoeneberger et al. 2012). Of these agroforestry options, incorporating field and farmstead windbreak practices into farm management plans is a very promising option for reducing emissions from the farm operation, along with directly sequestering in its biomass.

Planting field windbreaks on agricultural lands reduces the cropping area, but generally more than compensates for this loss by increasing crop yields (Caborn 1957, Stoeckler 1962, van Eimern et al. 1964, Grace 1977, Kort 1998, Sun and Dickinson 1994, Hodges et al. 2004). By reducing the area of land being farmed windbreaks lead to a reduction in fuel and other inputs and is referred to as “avoided emissions” as well as indirect benefits (Brandle et al. 1992). Avoided emissions via windbreaks on farms can also be achieved through the use of living snow fences which reduces the need to clear snow from roads following snow events and thereby reduce fuel use (Shaw 1988, Scholten 1988) and through the use of farmstead windbreaks which reduce energy needs for home heating and cooling (Mattingly et al. 1979, Harrje et al. 1981, DeWalle and Heisler 1988, Moyer 1999). Readers are referred to www.nac.unl.edu for more information on windbreaks and these services.

Only limited work on the indirect impacts of agroforestry practices on the carbon budget of a farm has been done as compared to direct C storage in the woody biomass of windbreak trees. However, preliminary calculations by Brandle et al. (1992) suggest that the contribution of avoided emissions to the C budget may be even greater than these direct contributions. The objective of this study was to assess the indirect C effects of field and farmstead windbreaks and the magnitude of these values when compared to the carbon equivalent farm budget.

Materials and Methods

Overview

The crop budgets assessed corresponded to corn, soybean, potato and winter wheat operations; crop systems currently being used in Nebraska, Tennessee, Ohio, Montana, Texas, Iowa, Wisconsin, Idaho, Colorado, and Kansas (Appendix Table E-1). Reported data from these locations and crop systems were used to estimate C equivalent (CE) emissions (Appendix Table E-2 to E-5). Because the energy use for irrigation was considerable, these crops were grouped as irrigated and dryland crop operations.

The data from the Residential Energy Consumption Survey (RECS) made for the U.S. Energy Information Administration (USEIA 2009) were used to estimate farmstead size and use of electricity, natural gas, propane, and other fuels in different climatic zones (Figure 5.1). It was assumed that 5 percent of the crop area was removed from production and occupied by field windbreaks (Brandle et al. 1992). From these areas, the reduction of fuel, fertilizer and pesticide use was calculated.

The available data in the crop budgets for energy use are reported in different units, such as volume, (ml, gal, L), weight (oz., kg, Mg, cwt), units of energy (BTU) and electricity (kWh). To standardize these units, the carbon equivalent (CE) approach developed by Lal et al. (2004) and the Farm Energy Analysis Tool (FEAT) by Camargo et al. (2013) were used.

Using these values, the reductions in emissions resulting from the adoption of field and farmstead windbreaks on small (60 ha), medium (300 ha) and large (600 ha) farms were calculated. Finally, these estimates were projected to a 1 million ha basis in each of the farm sizes.

Carbon Emissions for the Major Crops in the United States

Crop budget data for 58 regional cropping systems; including corn, soybean, potato, and winter wheat, were acquired from Crop Budget sheets from the University of Nebraska (2014), University of Tennessee (2014), University of Ohio (2014), University of Montana (2014), University of Texas (2014), University of Iowa (2014), University of Wisconsin (2014), University of Idaho (2014), University of Colorado (2014), and University of Kansas (2014). Emissions by field management activities (i.e., tillage, seeding, spraying, cultivation, irrigation, harvesting, drying, hauling, and transporting); production, transport and transfer of fertilizers (nitrogen, phosphorus, potassium and lime); pesticides (herbicides, fungicides and insecticides); and crop residue decomposition were converted into CEs (Lal 2004, Camargo et al. 2013, USEPA 2014a).

Emissions for fertilizers (N_2O, P_2O_5 and K_2O) were calculated based on the concentration of minerals, while emissions from pesticides were calculated based on their active ingredient as described on their commercial labels. Fuel emissions were calculated from diesel fuel used by machinery and irrigation pumps. When a pump was powered by electricity, we used the conversion factor of 0.16 to convert kW h^{-1} to CE (Table 5-1) (Lal 2004, Camargo et al. 2013, USEPA 2014a). With this information, potential savings for each crop system were determined based on the area taken out of production by field windbreaks which were derived in a previous study (Chapter 4 Appendix Table D-1).

Potential Carbon Emissions from Typical Farmsteads

The data from the Residential Energy Consumption Survey (RECS) were queried from the U.S. Energy Information Administration (USEIA 2009). Data from five different climatic zones were acquired from the U.S. Energy Information Administration (USEIA) and the American Institute of Architects (AIA) (USEIA 2009) see Figure 5-1 and Appendix Table E-6.

Because new homes consumed 21% less energy for space heating on average than older homes (USEIA 2009) rural homes over a range of ages (built before and after 2000) were subsampled from the general data. From this new database, fifteen variables were analyzed (Table 5-2). The energy units of these variables were converted from BTU to

kWh^{-1} of energy equivalent and then to kg CE using values listed in Table 5-1. The conversion from energy source to CE was based on the USEPA (2014a) protocol for estimating kg CE is described as follows:

1. Electricity: kWh per home × 1,232 lbs. CO_2 per megawatt-hour generated × (1/(1-0.072)) MWh generated / MWh delivered × 1 MWh/1,000 kWh × 1 metric ton/2,204.6 lb = metric tons CO_2 $home^{-1}$.
2. Natural gas: cubic feet per home × 0.0544 kg CO_2 cubic $foot^{-1}$ × 1/1,000 kg metric ton^{-1} = metric tons CO_2 $home^{-1}$.
3. Liquid petroleum gas: gallons per home × 1/42 barrels $gallon^{-1}$ × 219.3 kg CO_2 $barrel^{-1}$ × 1/1,000 kg metric ton^{-1} = metric tons CO_2 $home^{-1}$.
4. Fuel oil: gallons per home × 1/42 barrels gallon-1 × 429.61 kg CO2 barrel-1 × 1/1,000 kg metric ton-1 = metric tons CO_2 home-1.

All these energy sources were converted from CO_2 equivalent to kg CE by diving by 3.667.

The total carbon equivalent emissions calculated for rural homes are summarized and presented in Appendix Table E-7. Because windbreaks only have a significant effect on energy used for heating and cooling farmsteads, we use only the values for propane and electricity used for heating and cooling homes (Appendix Table E-8). Although the data were extensive, verified, and of high quality (USEIA 2009), some homes were disqualified based on the following:

- extreme outliers (more than four standard deviations away from the mean)
- uninsulated houses,

- households where the occupants neither owned nor paid rent (i.e. squatted), and
- farmsteads with wood as the primary source of heat.

It should be noted that many older homes were inadequately insulated and would benefit greatly from wind protection, but were eliminated from the analysis because they were few (less than 1%) and their main energy source was wood.

Reduced Carbon Emissions in Agricultural Lands by Planting Windbreaks

Carbon reduction emissions in the cropping area were calculated based on the area planted to field windbreaks and removed from production. To evaluate the effect of the windbreaks on energy savings for farmsteads, it was assumed that:

1. The windbreaks were planted perpendicular to the prevailing wind with a density of 40 – 60% (Brandle et al. 1988).
2. There were energy savings from air conditioning of 10% (Harrje et al. 1981, McPherson 1994) and of 25% for home heating (DeWalle and Heisler 1988, Brandle et al. 2009).
3. A farmstead area of 2 ha was defined for both small and medium farms. For large farms, an area of 3 ha was used. These farmsteads contained a house of 230 and 270 m^2 built before and after 2000, respectively (Appendix Table E-6). For full protection of the small and medium farmsteads, a 200 m windbreak is required. For large farms, a 300 m windbreak is needed. In northern zones, a 10-row windbreak is needed while in southern zones a 3-row windbreak is sufficient. Typically, these

windbreaks have two sections arranged in an “L-shaped” design and located north and west of the home to protect against winter winds.

4. Three farm sizes were considered: small (60 ha), medium (300 ha) and large (600 ha). This resulted in six scenarios (2 age groups of houses and 3 farm sizes). Values calculated are summarized and presented in Appendix Table E-9.

Data Analysis

The data were processed under the R environment (CRAN 2014) and Microsoft Excel. The data for the Residential Energy Consumption Survey (RECS) were sub-sampled for rural houses and analyzed for built age (before and after 2000). Descriptive statistic was used for grouping the 58 cropping systems (See Appendix Table E-1) in irrigated and dryland operations across climatic zones (See Figure 5.1) to determine their emissions (See Figure 5.2) and carbon emissions avoided for each farming scenario.

Results

Carbon Emissions for the Major Crops and Farmsteads in the United States

Carbon emission estimates for the cropping systems used in this study varied among regions. These emissions from fossil fuels, materials and crop residues ranged from 0.16 (Appendix Table E-3) to 1.5 Mg CE ha^{-1} (Appendix Table E-5) for the various cropping scenarios. Potato systems showed the highest emissions per hectare (1.01 to 1.51 Mg CE ha^{-1}) (Appendix Table E-5), followed by corn systems (0.25 to 0.81 Mg CE ha^{-1}) (Appendix Table E-2); winter wheat systems (0.16 to 0.53 Mg CE ha^{-1}) (Appendix Table E-4); and finally soybean systems (0.16 to 0.33 Mg CE ha^{-1}) (Appendix Table E-

3). The amount of CEs emitted will depend of the decisions that farmers make when managing different crop systems. Mean CE estimates of the irrigated and non-irrigated crop systems in the studied areas are displayed in Figure 5.2. In these values, the main difference in the energy use comes from the use of diesel fuel and fertilizers in potato and corn systems.

No significant differences were found between houses built before and after 2000 for emissions. Total emissions for the average farmstead are summarized in Appendix Table E-4. These data include all possible energy uses by the home. They range from 1. 4 to 4.1 Mg CE yr^{-1} $house^{-1}$ for electricity; 0.7 - 2 Mg CE yr^{-1} for natural gas; 0.4 - 3.7 Mg CE yr^{-1} $house^{-1}$ for propane; and 0.0 to 2.5 Mg CE yr^{-1} $house^{-1}$ for fuel oil.

The main sources of energy for heating and cooling farmsteads were electricity and propane. The CE emissions for space heating and cooling across regions ranged from 1.4 to 2.3 Mg CE $house^{-1}$ (Appendix Table E-5) for all age groups of houses. As expected, the better the insulation the lower the CE emitted for farmsteads in all regions. It was found that despite the higher energy demand for spacing heating in southern homes, the trend in northern homes was to emit more CE per home. This is because a typical central air conditioner is about four times more energy efficient than a typical furnace or boiler (Sivak 2013). These results indicate that home heating in cold climates is more energy demanding than living in warm climates. According to USEPA (2014 b), electricity generation for fossil fuel-fired power plants is responsible for 40 percent of carbon dioxide emissions from the combustion of fossil fuels in the United States.

Reduction of Emissions by Windbreaks on Agricultural Lands

Overall, we estimated the use of field and farmstead windbreaks can reduce emissions from farming operations from a low of 0.01 Mg CE ha^{-1} yr^{-1} for some windbreak scenarios (e.g., soybean on small Arkansas farms) to a high of 0.7 Mg CE ha^{-1} yr^{-1} (e.g., large farm scenarios with potato in Massachusetts). Overall for all farm scenarios considered, the reduction in emissions attributable to windbreaks ranged from 0.9 to 39 Mg CE (Appendix Table E-9). The lowest reduced emissions occurred in scenarios containing soybean and winter wheat systems with the highest in potato systems (Appendix Table E-9). The mean reduced emissions, for small and large farms, were equivalent to 0.02 to 0.05 Mg CE ha^{-1} yr^{-1}, respectively.

Potato farming scenarios with windbreaks for all regions analyzed had the greatest reduction in emissions (Appendix Table E-9). Potato crops are highly intensive in the use of fuel and chemicals, especially nitrogen. These potential reductions in were estimated to be between 3.3 and 39.1 Mg CE for small and large farms containing a farmstead built either before or after 2000. On a per hectare basis, potential reductions in emissions for farming scenarios with windbreaks were 0.05 and 0.07 Mg CE ha^{-1}, for small and large farms, respectively.

Reduced emissions for corn farming scenarios with windbreaks ranged from 1.2 to 24.7 Mg CE for small and large farms, respectively. When furrow irrigated, corn on large farms displayed the highest avoided emissions (24.7 Mg CE) (Appendix Table E-9). On a per hectare basis, emissions ranged from 0.02 to 0.04 Mg CE ha^{-1} for small and large farms, again with no significant differences between farmsteads built before and after 2000.

Avoided emission for soybean farming scenarios with windbreaks were 0.8 and 9.6 Mg CE for small and large farms, respectively. The highest emission reduction values occurred in the Corn Belt region (Iowa) for herbicide-tolerant soybean. The lowest reduction of emissions by windbreaks corresponded to dryland soybean in the Corn Belt (Ohio) (Appendix Table E-9). These reduced CE emission scenarios were equivalent to 0.01 and 0.02 Mg CE ha^{-1} for small and large farms, respectively.

Reduction of carbon equivalent emissions of windbreaks on winter wheat farming scenarios ranged from 0.9 to 15.6 Mg CE for small and large farms, respectively. The highest reduction was found in dryland winter wheat under conventional tillage and fallow rotations, while the lowest reduction was found for sprinkler-irrigated continuous wheat in the Rocky Mountains South (Colorado). Overall, reduced emissions on these farms were equivalent to 0.02 and 0.03 Mg CE ha^{-1}.

The C emissions for farming scenarios on irrigated and non-irrigated crop systems on small and large farms are summarized on Table 5-3. The avoided C emissions after planting windbreaks on 5% of area of the irrigated and dryland farming scenarios are presented in Table 5.4. Windbreaks provided the largest potential reduction in C emissions in irrigated potato systems while their contributions in the rainfed winter wheat systems were the least. This was most likely due to the large amounts of fertilizer and fuel used in potato systems that were then partially reduced by use of field windbreaks.

From these results, we then calculated the potential reduction in C emissions for a national windbreak program encompassing 1 million ha (2.47 million acres) of agricultural lands. A program designed to establish windbreaks on 17,000 small; 3,300 medium; or 1,700 large farms would plant approximately 0.05 million ha (0.12 million acres) to windbreaks thereby removing that area from production. Over a year's cropping cycle, emissions ranging from 9,660 to 65,363 Mg CE yr^{-1} could potentially be avoided (Table 5.5). During the 50-year lifespan of the windbreaks, we could expect a reduction in emissions on the order of 0.5 and 3.3 Tg CE.

Discussion

The indirect benefits of windbreaks in terms of avoided C emissions resulted from the reduced use of fossil fuels and other energy-intensive inputs. By providing protection to different crop systems and farmsteads windbreaks cut the use of fuel and agricultural inputs by almost 5% and reduced the use of energy for heating and cooling farmsteads by 10 to 25% as reported by DeWalle and Heisler (1988), Heisler (1991), Brandle et al. (1992) and

The potential for farmstead windbreaks was greatest in those areas with cold winter winds; however, farmsteads in all regions could potentially derive some level of benefits from properly designed windbreaks. Brandle et al. (1992) indicate that the greatest economic benefit was derived from the energy savings from the reduction in air infiltration rates. These results were corroborated in this study when our savings varied with climate conditions (locations) and the type of insulation.

On small farms the majority of emission avoidance is a result of the farmstead windbreak and the majority of the carbon stored is in the farmstead windbreak. Thus small farm scenarios are more likely to approach C neutrality, potentially storing and /or avoiding more than they emit. In contrast, the emissions due to the agricultural operation in large farm scenarios are much greater and require greater offset than can be potentially accomplished by farmsteads and field windbreaks alone.

Further reduction of emissions in such farming operations can be accomplished through inclusion of many other activities, such as soil conservation practices (Franzluebbers 2010, USDA-NRCS 2009, 2015); optimizing fertilizer use (Mistsch et al. 2001, Bielinski 2011, Clark et al. 2004); improving irrigation systems (Martin 2014); and reducing the energy use in farmsteads (Muratory 2013, USEPA 2015). In reality, for a farm operation to approach a net zero emission status, the strategic use of several of these activities will be required, with windbreaks being just one part of the solution

Windbreaks can indirectly reduce input use through the increase of crop productivity. The literature suggests that windbreaks can increase crop yields levels (Kort and Turnock 1999) above what would be necessary to compensate for the area withdrawn from crop production (Brandle et al. 1992). These authors indicated that this additional production will reduce the rate at which additional crop area will need to be added in the future to meet growing food needs. This could potentially lead to a further reduction in the use of fuel and fertilizer and therefore in reductions to atmospheric GHG levels. Adding all these reductions, windbreaks seem a promising strategy to mitigate the impact of agriculture in the global carbon budget.

Conclusions

The avoided C emissions from fewer acres farmed and less energy used for heating and cooling the farmstead make windbreaks a promising strategy for reducing the impact of agriculture in the global carbon budget. Reduced C emissions on farm scenarios containing windbreaks are highly influenced by home insulation, technological improvements, and cropping systems. On these farming scenarios, windbreaks can substantially reduce the amount of off-farm inputs used on farming operations and at the same time mitigate negative externalities of the farming operations such as pollution of water sources by pesticides and fertilizers (Pearce and Koundoury 2003).

References

Bielinski, M.S. 2011. Selecting the Right Nutrient Rate: Basis for Managing Fertilization Program, Hor. Technology 21(6):683-685.

Brandle, J.R., Wardle, T.D. and Bratton, G.F. 1992. Opportunities to increase tree plantings in shelterbelts and their potential impacts on carbon storage and conservation, Forests and Global Change, Edited by R.N. Sampson and D. Hair. American Forests, Washington DC, pp 157-175.

Brandle, J.R., Hintz, D.L. and Sturrock, J.W. (eds.). 1988. Windbreak Technology, Elsevier Science Publishers, Amsterdam, 598 p.

Caborn, J.M. 1957. Shelterbelts and microclimate, Forestry Commission, Bulletin No. 29, 135 p.

Camargo, G.G.T., Ryan, M.R. and Richard, T.L. 2013. Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool, BioScience 63:263-273.

Clark, W. Gellings, K. and Parmenter, E. 2004. Energy efficiency in fertilizer production and use, in: efficient use and conservation of energy, [Eds. Clark W. Gellings, and Kornelis Blok], in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK http://www.eolss.net/sample-chapters/c08/e3-18-04-03.pdf (7/7/2015).

CRAN, (Comprehensive R Archival Network) 2015. R project. http://cran.r-project.org/ (7/7/2015).

DeWalle, D.R. and Heisler, G.M. 1988. Use of windbreaks for home energy conservation, Agric. Ecosyst. Environ 22/23:243-260.

Franzluebbers, A.J. 2010. Soil organic C sequestration with conservation agriculture in the southeastern USA: Potential and limitations. http://www.fao.org/ag/ca/C%20Offset%20Consultation/CMEETING/3FULLPAPERSBYCONSULTATIONSPEAKERS/PAPERFRANZLUEBBERS.pdf (7/1/2015).

Grace, J. 1977. Plant response to wind, London, New York, Academic Press, 204 p.

Harrje, D.T., Buckley, C.E. and Heisler, G.M. 1981. Building energy reductions: windbreak optimization, J. Energy Div., Am. Soc. Civ. Eng 108(3):143-154.

Heisler, G.M. 1991. Computer simulation for optimizing windbreak placement to save energy for heating and cooling buildings. http://www.nrs.fs.fed.us/pubs/jrnl/1991/nrs_1991_heisler_001.pdf (7/8/2015).

Hodges, L., Suratman, M.N., Brandle, J.R. and Hubbard, K.G. 2004. Growth and yield of snap beans as affected by wind protection and microclimate manages due to shelterbelts and planting dates, Hort. Science 39(4):996-1004.

IPCC. 2013. Climate change: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental panel on climate change. Chapter 8, anthropogenic and natural. http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf (7/8/2015).

Kort, J. 1998. Benefits of windbreaks to field and forage crops, Agriculture Ecosystems and Environment 22/23:165-190.

Kort, J. and Turnock, R. 1999. Carbon reservoir and biomass in Canadian prairie shelterbelts, Agroforestry Systems 44:175-189.

Lal, R. 2004. Carbon emission from farm operations, Environment International 30:981-990.

Martin, D. 2014. Estimating the savings from improving pumping plant performance. University of Nebraska, Extension, 2 p.

Mattingly, G.E., Harrje, D.T. and. Heisler, G.M. 1979. The effectiveness of an evergreen windbreak for reducing residential energy consumption, ASHRAE Trans 85(2):428-443.

Mitsch, W.J., Day, J.W., Wendell Gilliam, P.M. Groffman, D.L. Hey, G.W. Wang, R. and Wang, N. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi river basin: Strategies to counter a persistent ecological problem, Bioscience 51:5.

Moyer, R.L. 1999. Shelterbelt benefit to home heating cost, Transactions of the ASAE, 33(6):2-10.

Muratory, M. 2013. Rural energy use and the challenges for energy conservation and efficiency. http://www.nardep.info/uploads/Brief17_RuralEnergyConservation.pdf (7/8/2015).

Pearce, D. and Koundoury, P. 2003. Fertilizer and pesticide taxes for controlling non-point agricultural pollution, Agriculture and Rural Development, The World Bank Group, 5 p.

Schoeneberger, M.M., Bentrup, G., de Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., Zhou, X. and Current, D. 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture, Journal of Soil and Water Conservation 67(5):128-136.

Scholten, H. 1988. Snow distribution on crop fields, Agric. Ecosyst. Environ 22/23: 363-380.

Shaw D.L. 1988. The design and use of living snow fences in North America, Agric Ecosyst Environ 22/23:351-362.

Sivak, T. 2013. Air conditioning versus heating: climate control is more energy demanding in Minneapolis than in Miami. http://iopscience.iop.org/1748-9326/8/1/014050/pdf/1748-9326_8_1_014050.pdf (7/9/2015).

Sun, D. and Dickinson. G.R. 1994. Wind Effect on windbreak establishment in Northern Australia, Tree Planter's Notes 45(2):72-75.

Stoeckler, J. H. 1962. Shelterbelt influence on Great Plains field environment and crops, USDA, Washington DC, Forest Service Product Research Paper 62, 2 p.

University of Colorado. 2014. Crop enterprise budgets. http://www.coopext.colostate.edu/abm/cropbudgets.htm (7/8/2015).

University of Idaho. 2014. Costs of production of crops. http://web.cals.uidaho.edu/idahoagbiz/enterprise-budgets/ (7/8/2015).

University of Iowa. 2014. Estimated costs of crop production in Iowa – 2014. http://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf (7/8/2015).

University of Kansas. 2014. Projected budgets. http://www.agmanager.info/crops/budgets/proj_budget/decisions/ (7/8/2015).

University of Montana. 2014. Crops cost of production. http://www.montana.edu/softwaredownloads/cropdownloads.html (7/8/2015).

University of Nebraska (Klein, N.R). 2014. Nebraska crop budgets. http://www.ianrpubs.unl.edu/epublic/pages/publicationD.jsp?publicationId=597 (7/8/2015).

University of Ohio. 2014. Research: Farm Management Enterprise Budgetshttp://aede.osu.edu/research/osu-farm-management/enterprise-budgets (7/8/2015).

University of Tennessee. 2014. Field crop budgets. http://economics.ag.utk.edu/budgets/2014/2014RowCropBudgets.pdf (7/8/2015).

University of Texas. 2014. Crops and livestock budgets. http://agecoext.tamu.edu/resources/crop-livestock-budgets/ (7/8/2015)

University of Wisconsin. 2014. Enterprise budgets: Field crop enterprise budgets for 2014. http://www.uwex.edu/ces/farmteam/budgets/fieldcrop.cfm (7/8/2015).

USEIA, (US Energy Information Administration) 2009. Residential Energy Consumption Survey, Data: Microdata (RECS) http://www.eia.gov/consumption/residential/data/2009/index.cfm?view=microdata (7/8/2015).

USEPA, (US Environmental Protection Agency) 2014a. Calculations and references. http://www.epa.gov/cleanenergy/energy-resources/refs.html (7/8/2015).

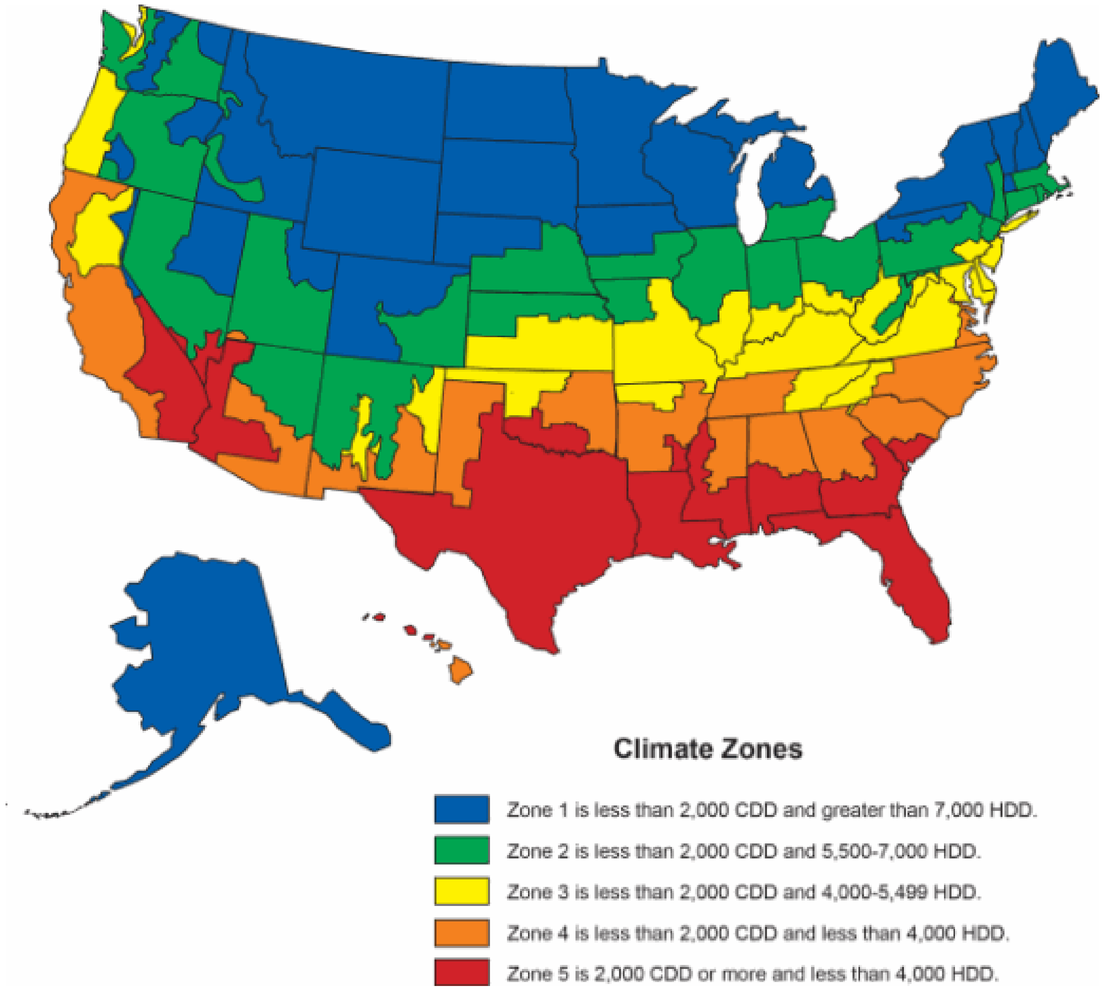
USEPA, (US Environmental Protection Agency) 2014b. Clean Energy.

http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html (7/8/2015).

USEPA, (US Environmental Protection Agency) 2015. Consumers choosing appliances. http://www.epa.gov/burnwise/choosing.html (7/8/2015).

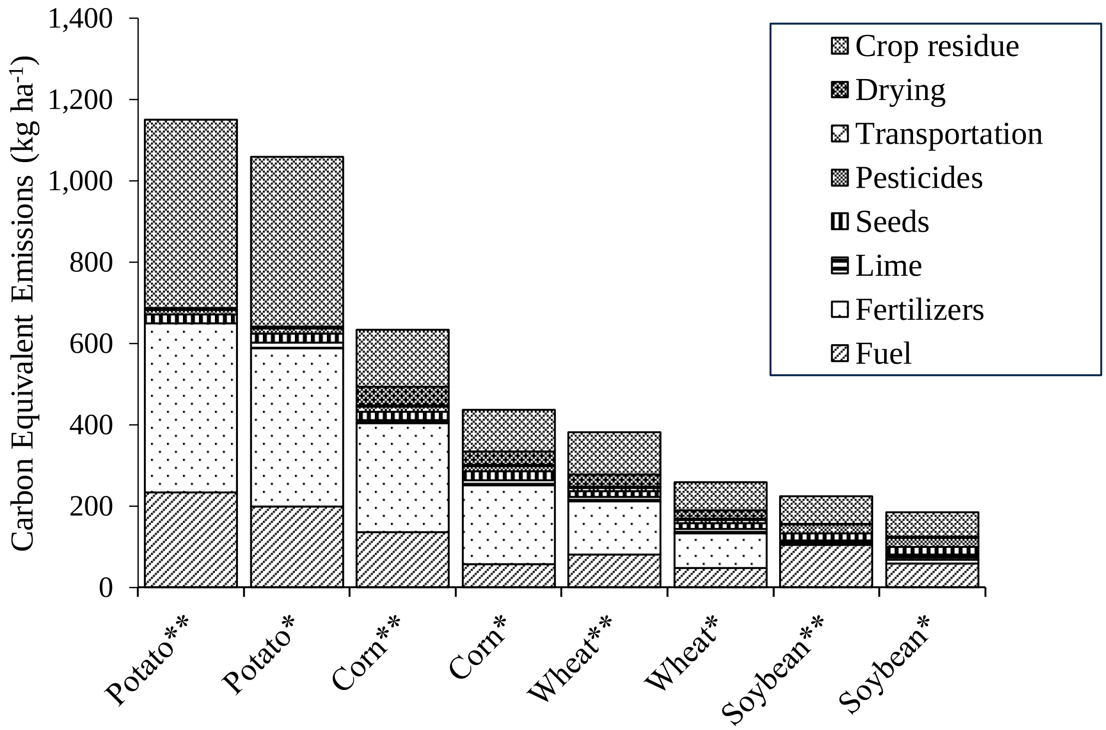
van Eimern, J., Karscho, R., Razumova, L.A. and Roberston, G.W. 1964. Windbreaks and shelterbelts, World Meteorological Organization, Technical Note No. 59, 188 p.

Figure 5-1. Climate zones in the continental United States.



Source: http://www.eia.gov/consumption/commercial/census-maps.cfm

Figure 5-2. Mean carbon equivalent emissions for the major crops in the nine regions of the United States derived from crop budgets (2014) in the sampled areas.



* Non-irrigated and **irrigated crop system.

Table 5-1. Values for converting energy source units to kg of carbon equivalents (kg CE).

Energy source	Units	Btu	KWh	Kg CE
Electricity	kWh	3,412.14	1	0.164
Natural gas	Cubic feet	1,030	0.30	0.164
Liquefied petroleum gas (LPG)	Gallon	91,600	26.85	0.164
Fuel oil	Gallon	139,000	40.74	0.164

Table 5-2. Description of variables selected from Energy Information Agency Microdata Code Book (USEIA 2009).

Number	Variable	Description
1	HDD30YR	Heating degree days, 30-year average 1981-2010, base 65F
2	CDD30YR	Cooling degree days, 30-year average 1981-2010, base 65F
3	AIA Zone	1. Less than 2,000 CDD and greater than 7,000 HDD 2. Less than 2,000 CDD and 5,500 - 7,000 HDD 3. Less than 2,000 CDD and 4,000 - 5,499 HDD 4. Less than 2,000 CDD and less than 4,000 HDD 5. 2,000 CDD or more and less than 4,000 HDD
4	YEARMADERANGE	Year range when housing unit was built 1. Before 1950 2. 1950 to 1959 3. 1960 to 1969 4. 1970 to 1979 5. 1980 to 1989 6. 1990 to 1999 7. 2000 to 2004 8. 2005 to 2009
5	ADQINSUL	Level of insulation (respondent reported) 1. Well Insulated 2. Adequately Insulated 3. Poorly Insulated 4. No Insulation
6	TOTSQFT	Total square footage (includes all attached garages, all basements, and finished/heated/cooled attics)
7	BTUELSPH	Electricity usage for space heating, in thousand BTU, 2009
8	BTUELCOL	Electricity usage for air-conditioning, central and window/wall (room), in thousand BTU, 2009

Table 5-2. (con't)

Number	Variable	Description
9	BTUNGSPH	Natural Gas usage for space heating, in thousand BTU, 2009
10	BTULPSPH	LPG/Propane usage for space heating, in thousand BTU, 2009
11	BTUFOSPH	Fuel Oil usage for space heating, in thousand BTU, 2009
12	BTUKERSPH	Kerosene usage for space heating, in thousand BTU, 2009
13	TOTALBTUSPH	Total usage for space heating, in thousand BTU, 2009
14	TOTALBTUCOL	Total usage for air conditioning, in thousand BTU, 2009
15	TOTALBTUOTH	Total usage for appliances, electronics, lighting, and miscellaneous uses, in thousand BTU, 2009

Table 5-3. Total carbon equivalent (Mg CE yr^{-1}) emissions estimates for irrigated and non-irrigated farming scenarios on farms containing adequately insulated houses built either before or after 2000.

Crop systems	Houses built before 2000[1]			Houses built after 2000		
	Small (60 ha)	Medium (300 ha)	Large (600 ha)	Small (60 ha)	Medium (300 ha)	Large (600 ha)
	Mg CE yr^{-1}					
Potato**	69.6	357.8	716.9	73.1	361.3	720.4
Potato*	56.6	291.1	583.1	60.1	294.6	586.6
Corn**	36.7	188.7	378.0	40.2	192.2	381.5
Corn*	25.3	129.9	260.2	28.8	133.4	263.7
Wheat**	21.5	110.6	221.6	25.0	114.1	225.1
Wheat*	15.0	76.9	154.1	18.5	80.4	157.6
Soybean**	14.1	72.6	145.4	17.6	76.1	148.9
Soybean*	10.6	54.6	109.4	14.1	58.1	112.9

** Irrigated * non-irrigated crop systems

Table 5-4 Scenarios for reduced carbon emissions (Mg CE) on small, mid and large size farms growing irrigated and non-irrigated crop systems and planting field and farmstead windbreaks.

Crop system	Houses built Before 2000[1]			Houses Built After 2000		
	Small (60 ha)	Medium (300 ha)	Large (600 ha)	Small (60 ha)	Medium (300 ha)	Large (600 ha)
	Mg CE yr^{-1}					
Potato**	3.86	18.27	37.22	3.79	18.20	39.15
Potato*	3.21	14.93	29.53	3.14	14.86	29.46
Corn**	2.22	9.81	19.28	2.14	9.74	19.21
Corn*	1.64	6.87	13.39	1.57	6.80	13.31
Wheat**	1.46	5.91	11.46	1.38	5.84	11.39
Wheat*	1.13	4.23	8.09	1.05	4.15	8.01
Soybean**	1.09	4.01	7.65	1.01	3.94	7.58
Soybean*	0.91	3.11	5.85	0.84	3.04	5.78

** Irrigated * non-irrigated crop systems

Table 5-5. Potential reduction in carbon emissions due to the use of windbreaks for various farming scenarios based on 1 million ha worth of farm at each size.

Crop system	Houses built before 2000			Houses built after 2000		
	Small[1] (60 ha)	Medium (300 ha)	Large (600 ha)	Small[1] (60 ha)	Medium (300 ha)	Large (600 ha)
	Mg CE yr^{-1}					
Potato**	65,363	61,104	60,572	64,139	60,859	60,450
Potato*	54,346	49,938	49,387	53,121	49,693	49,264
Corn**	37,453	32,816	32,237	36,229	32,572	32,114
Corn*	27,750	22,981	22,385	26,526	22,737	22,263
Wheat**	24,576	19,764	19,163	23,351	19,519	19,040
Wheat*	19,016	14,129	13,518	17,792	13,884	13,396
Soybean**	18,302	13,405	12,793	17,077	13,160	12,671
Soybean*	15,336	10,400	9,782	14,112	10,155	9,660

** Irrigated * non-irrigated crop systems

[1] Values based on the number of farms for each size that can be placed within a million ha: 17,000 (small), 3,300 (medium) and 7,700 (large)

CHAPTER 6: POTENTIAL CARBON BENEFITS OF WINDBREAKS ON FARMS OF THE UNITED STATES: FOUR REGIONAL SCENARIOS

Abstract

Windbreaks, especially field and farmstead windbreaks, can provide both direct (C sequestration) and indirect (avoided emissions) carbon (C) benefits within agricultural operations. To evaluate the level of impact by field and farmstead windbreaks on a farm's carbon (C) budget, twelve crop windbreak designs in four regions of the United States were constructed based off a typical farm and C emissions were calculated. Texas, Iowa, Nebraska and Idaho were selected to represent the Southern Plains, Corn Belt, Northern Plains, and Rocky Mountain regions, respectively. The typical farm in which the windbreaks were place was comprised of 600 ha (1,482 ac.); growing corn, soybean and winter wheat (Iowa, Nebraska, and Texas) or corn, winter wheat and potatoes (Idaho); having a farmstead of 3 ha (7.41 ac.); and containing a 250-m^2 house.

The lowest potential of windbreaks to offset CE emissions in the four regions and for the scenarios studied was found in Iowa (45 Mg CE yr^{-1}) [one-row field windbreak made of tall conifers and a five-row farmstead windbreak made of mixed trees]. The highest potential was found in Texas (139.9 Mg CE yr^{-1}) [three-row field and three-row farmstead windbreak, both made of mixed tree species]. The potential of the windbreak for offsetting CE emissions in the scenarios containing corn, soybean and winter wheat ranged from 22.4%, in Iowa (the Corn Belt) to 84 %, in Texas (the Southern Plains). In Idaho (Rocky Mountains North region) with the farm scenario containing corn, winter wheat and potato, the emissions offset by windbreaks ranged from 12% to 32%. Results

from this study indicate that field and farmstead windbreaks within agricultural operations have the potential to help offset C emissions in agricultural operations in the four regions studied.

Key words: Agroforestry systems, shelterbelt, climate change, energy use, carbon emissions, reduced carbon emissions, cropping systems.

Introduction

Agricultural systems have been identified as an anthropogenic activity that produces substantial amounts of greenhouse gases (GHG) (Johnson et al. 2005, Smith et al. 2014). It has also been identified as a means to also offset GHG emissions (CAST 2011). Reduced soil tillage (Frye 1984), optimized fertilizer production and use (Cole et al. 1997), improved irrigation techniques, enhanced solar drying and intensive animal husbandry (Chianese et al. 2009, IPCC 2013) are some of the many options that can minimize the impact of agricultural operations. These practices may reduce agricultural energy requirements by as much as 40% (Cole et al. 1997, Paustian et al. 1997). Combining trees and crops, which is referred to as agroforestry, is another strategy to mitigate GHGs, with agroforestry also having the added benefit of enhancing adaptation to climate change impacts (FAO 2010).

One specific category of agroforestry practices, windbreak, is especially appealing as an agricultural GHG mitigation activity. Windbreaks can store C in their above- and belowground biomass while reducing CO_2 emissions by protecting farmsteads, livestock, roads, people, soils and crops. Types of windbreaks include field, farmstead, livestock, and living snow fence (Skidmore 1986, Brandle et al. 1988, Buck et al. 1999). The capacity of windbreaks to sequester C in woody biomass in the United States is substantial (Udawatta and Jose 2011). However, the lack of data greatly limits our ability to quantify and thus evaluate the value of these windbreak services across geographic settings and different tree species. Likewise, we have a limited basis for understanding the extent and value of the indirect C impacts across regions that these plantings can provide via reductions in fuel use and energy savings. The objective of this study was to evaluate and compare the potential of field and farmstead windbreaks to offset emissions in different farming scenarios covering four regions of the United States.

Materials and Methods

Study Overview:

Many of the values used in calculating CE emission information in this study are reported in earlier studies (Chapter 3, 4 and 5). Data on C storage potential for different windbreak trees is listed in Table 3-7. The windbreak spacing used to design farm scenarios is listed in Table 4.1. Information relating the C emissions from corn, soybean, winter wheat and potato under different cropping systems can be found in Chapter 5 and Appendix Table E – 6; and emission data for heating and cooling farmsteads in different climate zones are listed in Chapter 5 Appendix Table E-8.

We selected four regions as representative of the areas with major crops planted, regions where windbreaks tend to be used and where there was relevant information of the tree species of concern in the FIA database. The regions selected included the

Northern Plains, the Corn Belt, Rocky Mountain North, and Southern Plains, with the test farms being located in Nebraska, Iowa, Idaho and Texas, respectively.

Carbon Storage Potential of Windbreaks on Farm Operations

Twelve tree species were selected taking into account their use in windbreaks in different regions. For our study these tree species were appropriate for the four regions studied. Using mean annual increment in diameter (MAID), Jenkins' et al. (2003) coefficients were used to determine the C stored in the woody biomass for each tree species (Table 6-2). Using these tree species, twelve field windbreaks and four farmstead windbreak designs were designed. The area of cropland removed from production by the different field and farmstead windbreak designs was determined for each farm. Carbon equivalent emission values reported in Appendix Tables E-2, E-3, E4 and E-5, for corn, soybean, wheat and potato systems, respectively, were used as a baseline from which the C impacts of windbreaks were then assessed. The C balance in each farming scenario was calculated by taking the C emitted by each farm scenario and subtracting the C stored by field and farmstead windbreaks and the avoided C emissions attained by planting windbreaks (Appendix Tables F-1 to F-4). These direct and indirect C benefits from windbreaks were then evaluated in terms of the potential emissions from each farming scenario and summarized in Table 6-3.

Carbon Budget Scenarios

To provide a more straightforward comparison of C values among the designs across the four regions the following assumptions were made:

- The area for a large farm comprised 600 ha (1,482 ac) and had a three-ha (7.41 ac) farmstead site containing an adequately insulated house built after 2000 of 250 m^2 (0.06 ac).
- For full protection of these farmsteads, a 300-meter, multi-row farmstead windbreak was required. This farmstead windbreak contained 3 rows in Texas, 5 rows in Nebraska and Iowa, and 10 rows in Idaho, and was located so as to provide protection during the winter months (Tables D-6 and D-7).
- The average windbreak height across regions was estimated at 25 ft. (7.6 m) for both deciduous and conifer species (Brandle et al. 2009). For eastern red cedar, height was estimated as 4 m (14 ft.).
- A farmstead windbreak can reduce C emissions from space cooling and heating by 10 to 25%, respectively (DeWalle and Heisler 1988. Carbon emissions for heating and cooling this house in the different regions and climate zones were derived from USEPA (2009) and are summarized in Table 6-1. With these estimates, the effects of different farmstead windbreak scenarios for the farm's net C emissions were calculated.
- Carbon storage potential for windbreak tree species was based on their local mean annual increment in diameter (MAID) over a 50-year lifespan. MAID values were taken from values calculated in an earlier study and can be found in Appendix Tables C-2.2, C-2.3, C-2.6 and C-2.9.

The C numbers were calculated for three different farm scenarios containing corn, soybean, winter wheat crops (Iowa, Nebraska and Texas) and one containing winter corn, soybean and potato crops (Idaho). The impact values as determined by field windbreak design in the offsetting of C emissions were then calculated in order to examine the variability and extent of windbreak contributions as a C mitigation option in different regions.

Results

Carbon Budget Scenarios on Agricultural Lands

Overall, the values of potential C stored and emissions avoided by different field windbreak designs in farms operations indicate that windbreaks can provide a substantial C offset in regards to the emissions generated by the agricultural operations evaluated here (Table 6-3). The potential of field and farmsteads windbreaks to store and reduce C in the four regions ranged from 45 to 176.7 Mg CE yr^{-1}, depending on field windbreak design and region. The lowest value was reported for a one-row field windbreak with tall conifers and a ten-row farmstead windbreak of mixed tree species in Iowa while the largest value were from a three-row field windbreak and a three-row, mixed-species farmstead windbreak scenario in Idaho (Table 6-3).

The potential C storage and emission reduction values for the windbreak designs used in this study were large enough to indicate they could potentially provide a significant C contribution, offsetting a large portion of the C emissions generated by corn, soybean and winter wheat operations. These C offset values by field windbreaks ranged from 21% in the Corn Belt (Iowa) to 84 % in the Southern Plains (Texas) for one and three-row windbreaks, respectively (Table 6-3). In the farm operations containing corn, winter wheat and potato in the Rocky Mountains North (Idaho), the emissions offset by windbreaks range from 16% to 50% for a one-row tall conifer windbreak and a three-row mixed species windbreak, respectively. The C storage potential of farmstead windbreaks (See Chapter 4 Table 4-7) was substantial in terms of being able to offset the average rural home emissions for heating and cooling (1.5 – 2.1 Mg CE home^{-1}) (Table 6.1).

Discussion

The amount of direct and indirect C benefits field and farmstead windbreaks can potentially confer, regardless of arrangement, is strongly affected by the growth rates in the different regions (Table 6-3). Some of the more promising tree species in several ecoregions were not included in our analysis due to the lack of growth and/or biomass data. This lack of information was most notable for the Rocky Mountain North region (Idaho). For more information about tree species performance the reader is referred to Table 6.2. We know that many coniferous and deciduous trees have the potential to grow well in most of regions studied (Oliver and Rycker 1990). For example, *Populus deltoides,* and *Pinus ponderosa* are trees with high biomass storage potential (van Haverbeke 1990, Kort and Turnock 1999). Assuming the growth rate reported by Kort and Turnock (1999) for hybrid poplar (11.1 kg yr^{-1} tree^{-1}) during 33 years, the potential C benefits of windbreak designs containing this tree species would could increase substantially.

The relative ability of all windbreak designs to offset the agricultural emissions generated within the farm they are place was affected by the type of farming system and the region in which it was located. Potato operations, for instance, have high CE emission values due to its high C input costs. On the other hand, corn, soybean and winter wheat are less intensive in the use of fertilizer, fuel and pesticides. Regardless of the relative ability of windbreaks (alone) to offset a farm's emissions as we've reported in this study, windbreaks as a management activity on farms need to be considered in terms of both the C and non-C benefits they can confer, especially when combined with other management activities on the farm that can then push the operation towards a more favorable C footprint and greater production and resiliency.

The acceptance and adoption of windbreaks within agricultural operations is very dependent on the reality that whatever services they provide, they must offset that production lost by the area taken up by the windbreak planting (s). In this study, windbreaks that took close to 5% of the land out of production could potentially reduce emissions from 16 to 65% of a total farm's carbon footprint (See Table 6.3). This would suggest that windbreaks would be a highly viable option to mitigate GHGs, and when combined with the other management activities that farmers have at their disposal, could be very effective in farms attaining a net zero operation.

The findings from this study suggest that in most cases two and three-row crop windbreaks took more land than the economic threshold of 5% of the cropland, as proposed by Brandle et al. (2009). This economic threshold is based on crop production and not on the many other services, including C that windbreaks can confer. This raises the question about how windbreak designs and farm management can be optimized to achieve environmental and productivity goals. There are many trade-offs between attaining favorable C footprint and production which have to be taken into account by farmers, decision makers and governments. In some cases C markets might help to make natural resource decisions more effective, efficient, and defensible (Nelson et al. 2009).

Windbreaks are one way to help reduce energy consumption from space conditioning and farming systems. A properly designed landscape can make a farm significantly more energy-efficient generating a lower C footprint in a way that also creates a more aesthetical and climate-pleasing environment. Combining field and farmstead windbreaks, where appropriate, appears to be a viable strategy for enhancing crop yields and living conditions while contributing towards more C neutral farming operations. Given these practices also have potential to provide climate change adaptation services (Schoeneberger et al. 2012), windbreaks deserve serious consideration in the formulation of management strategies for GHG mitigation on farms of the United States.

Conclusions

The values calculated for C reduction and storage by different field windbreak designs along with a farmstead windbreak indicate that windbreaks can make substantial contributions towards decreasing a farm’s C footprint. Using the approach we developed for assessing these contributions by windbreaks, we found that two and three-row windbreak designs can potentially offset most of the emissions from the farm scenarios containing corn, soybean and winter wheat. By integrating windbreaks along with other farm management practices, such as crop rotations, minimum tillage, cover crop systems, optimized fertilizer's application, and farmstead improvements into farm systems, farmers should be able to have more carbon efficient agricultural systems. As implementation is at the farm level, estimates of C emissions and reductions by management activity options are needed at the farm-scale to help all involved decision makers, from the person managing the land to those developing climate change programs and policies, compare the options and develop sound strategies.

Methodologies and decision-support tools and models have been developed to support producer-level GHG estimation for potential use in GHG mitigation policies, as well as voluntary emissions offset markets and more are under development (Eve at al. 2014). Those for agroforestry are limited (Ogle et al. 2014). This study provides a first approximation for regional assessments of field and farmstead windbreaks. While many factors were considered in our calculations, some were not, such as the amount of C emissions for production, transport and storage of the inputs off-farm. These as well as other components within the farming operation will need to be included as we strive to develop a more comprehensive life cycle analysis of windbreak's C contributions within U.S. agriculture. As such, numbers calculated in this study are conservative; an underestimation of windbreak's C benefits to farm well-being. Assessing the C contributions of windbreaks, as well as other agroforestry practices, to U.S. agriculture will continue to advance as research progresses.

References

Bowler, L. 2002. Developing sustainable agriculture, Geography 87:205-212.

Brandle, J.R., Hintz, D. L. and Sturrock, J.W. 1988. Windbreak Technology, Elsevier Science Publishers, Amsterdam, 598 p.

Brandle, J.R., Wardle, T.D. and Bratton, G.F. 1992. Opportunities to increase tree plantings in shelterbelts and their potential impacts on carbon storage and conservation, Forests and Global Change, Edited by R.N. Sampson and D. Hair. American Forests, Washington DC, pp 157-175.

Buck, L., Lassoie, J. and Fernandes, E. 1999. Agroforestry in sustainable agricultural systems, CRC Press, Boca Raton, FL, 416 p.

Chianese, D.S., Rotz, C.A. and Richard, T.L. 2009. Simulation of C dioxide emissions from dairy farms to assess greenhouse gas reduction strategies, Trans ASAE 52:1301-1312.

Cole, C. V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, K. and Zhao, Q. 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture, Nutrient Cycling in Agroecosystems 49(1-3):221-228.

Council for Agricultural Science and Technology (CAST) 2011. C sequestration and greenhouse gas fluxes in agriculture: Challenges and opportunities, Task Force Report, No. 142, 106 p.

DeWalle, D.R. and Heisler, G.M. 1988. Use of windbreaks for home energy conservation, Agric. Ecosyst. Environ 22/23:243-260.

Ellis, E.A., Bentrup, G. and Schoeneberger, M.M. 2004. Computer-based tools for decision support in agroforestry: current state and future needs. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1003&context=usdafsfacpub (7/9/2015).

FAO, (Food and Agriculture Organization of the United Nations) 2010. “Climate-Smart” Agriculture policies, practices and financing for food security, adaptation and mitigation. http://www.fao.org/docrep/013/i1881e/i1881e00.pdf (7/9/2015).

Frye, W.W. 1984. Energy requirements in no tillage. In: No-tillage Agricultural Principles and Practices. Phillips, R.E and Phillips, S.H. (eds.), pp 127-151.

IPCC, (Intergovernmental Panel on Climate Change). 2013. Climate change: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental panel on climate change, Anthropogenic and natural. http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf (7/8/2015).

IPCC, (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: Synthesis Report. https://www.ipcc.ch/publications_and_data/ar4/syr/en/spms4.html (7/8/2015).

Johnson, J.M.F., Reicosky, D.C., Allmaras, R.R., Sauer, T.J. Venterea R.T. and Dell. C.J. 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA, Soil & Tillage Research 83(1):73-94.

Kort, J. and Turnock, R. 1999. C reservoir and biomass in Canadian prairie shelterbelts, Agroforestry Systems 44:175-189.

Nair, P.K.R. 2011. C sequestration studies in agroforestry systems: a reality-check. Agroforestry Systems 86:243-253.

Nelson, E., Mendoza, G., Regetz, J., et al. 2009. Modeling multiple ecosystems services, biodiversity conservation, commodity production, and tradeoffs at landscape scale. https://www.uvm.edu/giee/pubpdfs/Nelson_2009_Frontiers_in_Ecology_and_the_Environment.pdf (7/8/2015).

Oliver, W.W. and Rycker, R.A. 1990. Ponderosa pine. In: Silvics of North America: 1. Conifers. Burns, Russell, M and Honkala, B.H. (Tech. Coords.), Agriculture Handbook 654.U.S. Department of Agriculture, Forest Service, Washington DC, 2:877.

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., van Noordwijk, M. and Woomer, P.L. 1997. Agricultural soils as a sink to mitigate CO_2 emissions, Soil Use Manage 13:1-15.

Schoeneberger, M.M., Bentrup, G., de Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., Zhou, X .and Current, D. 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture, Journal of Soil and Water Conservation 67(5):128-136.

Schoeneberger, M.M. 2009. Agroforestry: working trees for sequestering carbon on agricultural lands, Agroforestry Systems 75:27-37.

Smith P., Bustamante, M.A., Hammad, H., et al. 2014. Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 822-825.

Skidmore, E.L. 1986. Wind erosion control. Climatic Change 9:209-218.

Torquebiau, E. 2013. Agroforestry and climate change, FAO webinar. http://www.fao.org/climatechange/36110-0dff1bd456fb39dbcf4d3b211af5684e2.pdf (7/8/2015).

USEPA, (U.S. Environmental Protection Agency) 2009. Residential Energy Consumption Survey, Data: Microdata (RECS). http://www.eia.gov/consumption/residential/data/2009/index.cfm?view=microdata (7/8/2015).

van Haverbeke, D. 1990. Eastern Cottonwood. In: "Silvics of North America" http://www.na.fs.fed.us/spfo/pubs/silvics_manual/volume_2/populus/deltoides.htm (7/13/2015).

Table 6-1. Carbon emissions (Mg CE yr^{-1}) for heating and cooling for an adequately insulated farmstead (250 m^2) in different regions and climate zones of the United States.

Region	State	Climatic Zone[1]	Mean farmstead emissions (Mg CE yr^{-1})		
			Heating	Cooling	Total
North Lake States	Wisconsin	1	1.7	0.1	1.8
Corn Belt	Ohio	2	1.4	0.1	1.5
Corn Belt	Iowa	2	1.4	0.1	1.5
Southern Plains	Texas	5	1.1	1.0	2.1
Delta States	Arkansas	4	1.2	0.5	1.7
Appalachia	Tennessee	4	1.2	0.5	1.7
Rocky Mountains North	Idaho	1	1.7	0.1	1.8
Rocky Mountains South	Colorado	1	1.7	0.1	1.8
North East	Massachusetts	1	1.7	0.1	1.8
Northern Plains	Nebraska	2	1.4	0.1	1.5

Source: Derived from survey of DOE (2009)
[1] Climate zone – see figure 5.1

Table 6-2. Regional carbon storage potential (Mg C tree^{-1}) (based on 50 years) for different windbreak-suitable tree species in the United States.

Tree species	Carbon storage potential[1] (Mg C tree 50 yr^{-1})			
	Southern Plains (Texas)[2]	Corn Belt (Iowa)	Northern Plains (Nebraska)	Rocky Mountain North (Idaho)
Juniperus virginiana	168.2±1.9	154±10	121.7±32.5	83.74±45.2
Pinus contorta	-	-	-	91.1±56.8
Pinus ponderosa	-	-	169.2±40	139.1±7.5
Pinus strobus	-	110.3±22	-	-
Pinus taeda	178.2±30.3	-	-	-
Celtis occidentalis	75.4±34.6	70.7±11.5	-	-
Fraxinus pennsilvanica	49.1±7.6	40.4±6.2	40.2±3.6	86±48.9
Populus deltoides	467.2±134	318.7±78.5	336.4±209.5	-
Ulmus Americana	48.7±13.8	80.4±9.4	62.8±8.1	-
Quercus alba	119.0±13.8	86.2±12.4	-	-
Quercus macrocarpa	81.6±20.1	84.6±25.2	83.5±20.6	-
Quercus rubra	-	113.2±14.6	86.2±12.4	-

Source: FIA dataset.
[1]Value derived from tree MAID for trees with ages between 10 and 50 year.

Table 6-3. Total carbon equivalent (CE) emissions from 600-ha farms with different cropping systems in four regions of the United states and the potential C offset values afforded by different windbreak designs for these farms.

Field Windbreak designs	Total (Mg C yr^{-1})			
	Southern Plains (Texas)[1]	Corn Belt (Iowa)[1]	Northern Plains (Nebraska)[1]	Rocky Mountain North (Idaho)[2]
Total CE emissions[3]	(167)	(214)	(261)	(350)
One row small coniferous	108.9[4]	116.3	92.8	76.5
One row tall deciduous	62.0	45.2	46.2	85.7
One row tall coniferous	52.6	45.0	53.7	56.2
Two rows tall deciduous[5]	79.45	59.7	59.8	111.8
Two rows tall coniferous	81	70.2	81.8	88.5
One row tall coniferous and one row tall deciduous	80.9	65.5	71.6	100.6
One row tall coniferous and one row small conifer	129.5	130.3	116.0	105.6
One row tall deciduous and one row small conifer	130.3	127.2	107.0	117.1
Three rows tall coniferous	133.9	114.1	134.0	141.3
Three row tall deciduous	128.3	94.3	94.8	176.7
Two rows tall deciduous and one row tall coniferous	129.5	100.5	107.6	163.8
One row tall deciduous, one row tall coniferous and one row small coniferous	139.9	127.0	121.5	145.2

[1] Calculations for a 600 ha farm growing corn, soybean and winter wheat systems, each on 1/3 of the cropland area, with a farmstead of 3 ha containing a house of 250 m^2 protected by a 300 m long 3 (Southern Plains to 10-row windbreak (other).

[2] Calculations for a 600 ha farm growing corn, soybean, winter wheat and potato systems

[3] Carbon equivalent emissions on farming scenario.

[4] Carbon stored plus avoided by farmstead and field windbreaks. To get the offset percentage divides the CE offset by the CE emissions per farm.

[5] Designs of two and three row windbreaks included 6 m spacing between rows. See Appendix Table D-1 and D-2.

.

CHAPTER 7: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

Agricultural activities are unique in that they can both produce and mitigate emissions. As the demand increases for these lands to produce even more food, it will be imperative that farmers have access to management activities that can assist them in meeting production goals in ways that support resilient operations and that reduce GHG emissions. We demonstrated that in four regions of the United States where windbreaks make sense in terms of non-GHG services that they can also provide substantial C offset contributions.

Crop production systems are an important driver of the economy in the United States, but these agricultural activities unquestionably increase greenhouse gas (GHG) concentrations in the atmosphere. Unfortunately, the amount and intensity of the fuel and inputs used have had a significant impact in the national GHGs budget. Today, agricultural emissions of GHGs are rising and thus, significantly contributing to climate change (IPCC 2013). To keep the food system running while reducing its carbon footprint, different strategies are needed to adapt and mitigate these climate change threats. To achieve that goal, many tools are available and others are being developed (Ellis et al. 2004). One of available tools are windbreaks, which have proven their potential for reducing GHG emissions and storing carbon in agricultural lands, while increasing yield and offering other benefits (Brandle et al. 2009).

This study evaluated the potential of the windbreaks to store carbon and reduce GHG emissions on farms in different regions of the continental United States, using data obtained from US-FIA, USDA, US-EIA, USDA NRCS, national crop budgets, and other sources. This information was focused on windbreak tree species, C storage potential, avoided emissions, and windbreak design. The main aspects addressed in this study are: 1) methods for estimating C storage potential for windbreaks, 2) the potential values for C sequestered and avoided C emissions by windbreaks on agricultural lands, and 3) the potential magnitude of these windbreaks in regards to offsetting C emissions from different farming scenarios for different regions. Data were analyzed using quantitative analysis, which included analysis of variance (ANOVA) and Model Selection Analysis (MSA). ANOVA detected differences among biomass/C potential of the tree species in the different ecoregions, while MSA selected the best model to estimate biomass/C storage from a tree in windbreak designs. Finally, different farm scenarios were evaluated in terms of C contributions afforded by use of field and farmstead windbreaks. Overall, results from these studies support the use of windbreaks as a viable strategy for mitigating C emissions on farms.

Until better information becomes available, we recommend the use of the Jenkins et al (2003) coefficients for estimating biomass potential for windbreak. The Jenkins model incorporated coefficients for each group of species, enabling the calculation of regional biomass storage values per windbreak. We recognize that local variations, could affect the accuracy of these estimates. For this reason, regional adjustment of these coefficients is recommended where possible in future efforts to reduce uncertainty.

Farming fewer acres means a reduction in fuel and inputs, thus reducing off-farm C impacts. Additionally, farmstead windbreaks are estimated to reduce home heating and cooling needs by 10 to 25%. The potential positive impacts of windbreaks found in this study support the use of these agroforestry systems as a GHG mitigation tool for agriculture.

The farming scenarios evaluated showed that well-designed and located windbreaks have the potential to offset C emissions on agricultural lands, thereby reducing a farm's C footprint. Despite some uncertainties with the regional performance of some tree species and their low-carbon storage rate in some cases, the overall performance of these tree structures make them a reliable tool for mitigating carbon emissions on farms.

Conclusions

Agroforestry is one of the many climate-change mitigation and adaptation tools needed for improving the resilience of agricultural lands under the uncertainties of climate change. There are no simple solutions to the complex challenges of food production and climate change effects. Current technological approaches are important, but are not enough to respond to the future environmental challenges. In this scenario, the importance of developing an agroforestry knowledge base in ways that explicitly recognize the complexity of issues behind crop production, economics, and environmental be key for achieving a technical sound and economically feasible agroforestry information and assistance.

Windbreaks as an agroforestry system, is a promising tool for helping to build a climate smart agriculture system. The C storage potential of the different windbreak designs and their capacity for reducing carbon emissions demonstrate that these arrays of trees can offset most of the C emissions on cropping systems while protecting homes, facilities, and crops.

Carbon neutral to near neutral farms were potentially possible under windbreak scenarios. Although, the performance and management regime of these tree structures can vary from one site to another, and the integration of windbreaks on croplands can be troublesome for many farmers, the values we found in our studies indicate the results will be worth the initial effort. Additional issues that will need to be addressed include how we can to reduce uncertainties linked to cropping yields and how to belter guarantee the residence time of windbreak woody products to extend C storage capacity.

Limitations in the data sets used throughout this analysis can lead to some variability in the final outcomes and introduce errors in the calculations. Despite these limitations, our estimates clearly indicate net gains in C benefits that support the promotion of windbreaks as a promising C mitigation tool in the United States.

Recommendations for Future Research

To contribute to the scientific basis for the strategic use of windbreaks in United States' agriculture, future research efforts should focus on:

- Developing a national scale comprehensive carbon storage report for windbreaks using adjusted coefficients of Jenkin's general equation
- Including windbreaks in some form of national inventory to obtain data on tree species distribution and growth, and land area under windbreaks for different ecoregions
- Developing protocols to deal with pest, diseases, and management of the most promising windbreak trees
- Evaluating different house, windbreak, and farm designs, and their contributions to the carbon balance
- Assessing the performance of windbreak trees and their capacity to provide C services, as well as others, under different climate-change scenarios
- Developing a tree-breeding program to develop and select for more climate change resilient plant materials for windbreak and other agroforestry plantings
- Building a more comprehensive understanding and quantification of the C footprint of whole farm operations that includes windbreaks, as well as other mitigation activities
- Identifying barriers to adoption by evaluating the willingness for farmers to adopt windbreak designs as a tool to face climate-change uncertainties

References

Brandle, J.R., Hodges, L., Tyndall, J. and Sudmeyer, R.A. 2009. Windbreak practices. In: North American Agroforestry, an integrated science and practice, Garrett, H.E. (ed.) 2nd American Society of Agronomy, Madison, pp 75-104.

Ellis, E.A., Bentrup, G. and Schoeneberger, M.M. 2004. Computer-based tools for decision support in agroforestry: current state and future needs. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1003&context=usdafsfacpub (7/9/2015).

IPCC, (Intergovernmental Panel on Climate Change). 2013. The physical science basis, Working group I contribution to the IPCC fifth assessment report. http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_TechnicalSummary.pdf (7/9/2015).

APPENDIX C. DIRECT CARBON STORAGE POTENTIAL FOR WINDBREAK TREE SPECIES.

Table C-1. Regression models from different sources for estimating above and belowground biomass storage in trees.

Model Id.	Author	Origin	Equation
3	Anurag et al. (1989)	India	log10 bm = a + b * (log10(dia^c))
9	Baskerville (1965)	New Brunswick	log10 bm = a + b * (log10(dia^c))
29	Chapman and Gower (1991)	Wisconsin	ln bm = a + b * dia + c * (ln(dia^d))
52	Freedman et al. (1982)	Nova Scotia	ln bm = a + b * dia + c * (ln(dia^d))
75	Honer (1971)	Ontario	ln bm = a + b * dia + c * (ln(dia^d))
80	Jokela et al. (1986)	New York	ln bm = a + b * dia + c * (ln(dia^d))
82	Ker (1980b)	Nova Scotia	ln bm = a + b * dia + c * (ln(dia^d))
102	Martin et al. (1998)	North Carolina	log10 bm = a + b * (log10(dia^c))
110	Naidu et al. (1998)	North Carolina	log10 bm = a + b * (log10(dia^c))
114	Pastor et al. (1984)	Eastern U.S.	ln bm = a + b * dia + c * (ln(dia^d))
119	Phillips (1981)	Southeast U.S.	bm = a + b * dia + c * (dia ^ d)
138	Schnell (1976)	Tennessee	bm = a + b * dia + c * (dia ^ d)
177	Young et al. (1980)	Maine	ln bm = a + b * dia + c * (ln(dia^d))
179	Xiao and Ceulemans (2004)	Belgium	bm = exp(a + b *ln(dia)
180	Vog and Siccama (1999)	Connecticut	bm= exp(a + b *ln(dia)
181	Jenkins et al. (2003) (abg)[2]	USA	bm = exp(a + b *ln(dia)
182	Jenkins et al. 2003 (ratio)	USA	ratio = exp(a + (b/dbh)
12462[1]	Wiant et al. (1977)	West Virginia	bm =a + b*dbh + b*dbh^c
12466[1]	Wiant et al. (1977)	West Virginia	bm a + b*dbh + b*dbh^c
12693[1]	Brenneman et al. (1978)	USA	bm= a + b*dbh + b*dbh^c
12099[1]	Perala et al. (1994)	USA	bm = a + b*dbh + c*dbh^d
12467[1]	Wiant et al. (1977)	West Virginia	bm =a + b*dbh +cb*dbh^d
10628[1]	Clark et al. (1986)	Tennessee	bm= a + b*dbh^2 + c*dbh^2^d

[1] code from FAO, CIRAD www.globallometree.org/

Table C-1. (con't)

Model Id.	Author	Origin	Equation
10313[1]	Clark et al. (1986)	Tennessee	bm= a + b*dbh^2 + c*dbh^2^d
8391[1]	Clark et al. (1986)	Tennessee	bm= a + b*dbh^2 + c*dbh^2^d
1000	This study1	NE, MT	sqrt(bm) = a + b* dbh
2000	This study2	NE, MT	sqrt(bm) = a + b* dbh + c*h

[1] code from FAO, CIRAD www.globallometree.org/

Table C-2.1. Mean annual increment in diameter (inches) for typical windbreak tree species in the North Lake States region.

Tree Species	Ecoregions		
	212	222	251
Ulmus americana	0.19 ± 0.00^{c}	0.24 ± 0.00^{b}	0.31 ± 0.02^{a}
Abies balsamea	0.12 ± 0.00^{a}	$0.10\pm.011^{a}$	NA
Populus deltoides	0.28 ± 0.03^{a}	0.29 ± 0.02^{a}	0.23 ± 0.05^{a}
Juniperus virginiana	0.11 ± 0.01^{a}	0.11 ± 0.005^{a}	0.10 ± 0.013^{a}
Pinus strobus	0.2 ± 0.003^{ab}	0.22 ± 0.003^{ab}	0.27 ± 0.15^{a}
Fraxinus pennsylvanica	0.1 ± 0.002^{a}	0.15 ± 0.003^{a}	0.15 ± 0.007^{a}
Celtis occidentalis	0.12 ± 0.04^{b}	0.22 ± 0.01^{a}	0.12 ± 0.02^{b}
Picea abies	0.12 ± 0.02^{b}	0.24 ± 0.02^{a}	NA
Pinus sylvestris	0.23 ± 0.02^{a}	0.21 ± 0.02^{a}	0.14 ± 0.05^{a}
Quercus alba	0.1 ± 0.00^{a}	0.1 ± 0.00^{a}	NA
Quercus macrocarpa	0.1 ± 0.00^{a}	0.1 ± 0.00^{a}	NA
Quercus rubra	0.15 ± 0.00^{a}	0.19 ± 0.00^{a}	NA

Means with the same letter are not significantly different
NA = Not available

Table C-2.2. Mean annual increment in diameter (inches) for typical windbreak tree species in the Corn Belt region.

Tree Species	Ecoregions			
	221	222	223	251
Ulmus americana	0.17±0.01^{c}	0.21±0.01^{b}	0.16±0.01^{c}	0.25±0.01^{a}
Abies balsamea	0.04±0.02	NA	NA	NA
Populus deltoides	0.30±0.04^{a}	0.31±0.02^{ab}	0.38±0.04^{a}	0.39±0.02^{a}
Juniperus virginiana	0.09±0.02^{b}	0.12±0.01^{b}	0.10±0.00^{b}	0.20±0.01^{a}
Pinus strobus	0.23±0.01^{b}	0.31±0.02^{a}	0.24±0.02^{b}	NA
Fraxinus pennsylvanica	NA	0.18±0.01^{a}	0.16±0.01^{a}	0.20±0.01^{a}
Celtis occidentalis	0.18±0.03^{a}	0.21±0.01^{a}	0.16±0.01^{ab}	0.21±0.01^{a}
Pinus taeda	0.31±0.04	NA	NA	NA
Picea abies	0.20±0.20^{a}	0.44±0.10^{a}	0.08±0.10^{b}	NA
Pinus sylvestris	0.17±0.014^{a}	0.13±0.02^{a}	0.08±0.10^{a}	NA
Quercus alba	.12±0.00^{a}	0.12±0.00^{a}	0.13±0.00^{a}	0.12±0.00^{a}
Quercus macrocarpa	0.15±0.02^{a}	0.13±0.01^{a}	0.14±0.03^{a}	0.13±0.01^{a}
Quercus rubra	0.23±0.01^{a}	0.23±0.01^{ab}	0.20±0.01^{b}	0.20±0.01^{ab}

Means with the same letter are not significantly different
NA = Not available

Table C-2.3. Mean annual increment in diameter (inches) for typical windbreak tree species in the Southern Plains region.

Tree Species	Ecoregions			
	223	231	232	255
Ulmus americana	0.18±0.04^{c}	0.20±0.02^{ac}	0.17±0.02^{b}	0.21±0.03^{a}
Populus deltoides	NA	0.55±0.1^{a}	0.83±0.23^{a}	0.72±0.16^{a}
Juniperus virginiana	0.13±0.002^{c}	0.18±0.001^{c}	0.35±0.04^{a}	0.20±0.001^{b}
Fraxinus pennsylvanica	0.19±0.04^{a}	0.16±0.01^{a}	0.17±0.01^{a}	0.17±0.01^{a}
Celtis occidentalis	0.16±0.03^{b}	0.10±0.04^{ab}	NA	0.12±0.07^{a}
Pinus taeda	NA	0.36±0.002^{a}	0.29±0.002^{b}	0.30±0.007^{b}
Quercus alba	0.13±0.01^{a}	0.20±0.06^{a}	NA	0.11±0.01^{a}
Quercus rubra	0.18±0.02^{a}	0.16±0.07^{a}	NA	0.14±0.01^{a}
Quercus falcata	0.14±0.03^{a}	0.18±0.01^{a}	NA	0.13±0.09^{a}

Means with the same letter are not significantly different
NA = Not available

Table C-2.4. Mean annual increment in diameter (inches) for typical windbreak tree species in the Delta States region.

Tree Species	Ecoregions			
	223	231	232	234
Ulmus americana	0.14±0.02[a]	0.19±0.01[a]	0.23±0.07[a]	0.20±0.01[a]
Populus deltoides	NA	0.38±0.08[a]	NA	0.48±0.04[a]
Juniperus virginiana	0.11±0.00[a]	0.15±0.00[a]	0.17±0.03[a]	0.15±0.02[a]
Fraxinus pennsylvanica	0.12±0.02[b]	0.16±0.01[b]	0.17±0.04[ab]	0.20±0.01[a]
Celtis occidentalis	0.15±0.02[a]	0.13±0.02[a]	NA	0.12±0.02[a]
Pinus taeda	0.29±0.01[c]	0.36±0.00[b]	0.35±0.00[b]	0.39±0.01[a]
Quercus alba	0.12±0.00[b]	0.13±0.00[b]	0.18±0.02[a]	0.14±0.1[ab]
Quercus rubra	0.14±0.00[a]	0.14±0.01[a]	0.13±0.08[a]	0.14±0.02[a]
Quercus falcata	0.15±0.01[a]	0.17±0.01[a]	0.17±0.02[a]	0.18±0.01[a]

Means with the same letter are not significantly different
NA = Not available

Table C-2.5. Mean annual increment in diameter (inches) for typical windbreak tree species in the Appalachia region.

Tree Species	Ecoregions			
	221	223	231	234
Ulmus americana	0.14±0.02[a]	0.13±0.01[a]	0.16±0.012[a]	0.16±0.04[a]
Populus deltoides	0.61±0.29[a]	0.22±0.29[ac]	0.48±0.06[abd]	0.73±0.10[acd]
Juniperus virginiana	0.11±0.020[a]	0.11±0.00[a]	0.11±0.01[a]	NA
Pinus strobus	0.19±0.01[a]	0.14±0.05[a]	0.19±0.15[a]	NA
Fraxinus pennsylvanica	0.13±0.02[b]	0.13±0.01[b]	0.20±0.01[a]	0.27±0.04[a]
Celtis occidentalis	0.17±0.01[a]	0.11±0.01[b]	0.24±0.03[a]	0.10±0.01[b]
Pinus taeda	0.37±0.01[a]	0.40±0.01[a]	0.32±0.01[b]	NA
Quercus alba	0.12±0.00[c]	0.13±0.00[b]	0.15±0.01[a]	NA
Quercus rubra	0.16±0.01[a]	0.19±0.01[a]	0.16±0.02[a]	0.23±0.06[a]
Quercus falcata	0.13±0.00[a]	0.12±0.01[a]	0.16±0.01[a]	NA

Means with the same letter are not significantly different
NA = Not available

Table C-2.6. Mean annual increment in diameter (inches) for typical windbreak tree species in the Rocky Mountains North region.

Tree Species	Ecoregions			
	331	332	333	342
Pinus ponderosa	0.22±0.02[a]	0.22±0.032[a]	0.35±0.18[a]	0.33±0.08[a]
Pinus contorta	0.30±0.01[a]	0.34±0.01[ab]	0.33±0.01[ab]	0.31±0.04[b]
Fraxinus pennsylvanica	0.31±0.01	NA	NA	NA

NA = Not available

Table C-2.7. Mean annual increment in diameter (inches) for typical windbreak tree species in the Rocky Mountains South region.

Tree Species	Ecoregions			
	313	321	331	341
Pinus ponderosa	0.29±0.02[a]	NA	0.26±0.04[a]	NA
Pinus contorta	NA	NA	0.06± 0.002	NA

Means with the same letter are not significantly different
NA = Not available

Table C-2.8. Mean annual increment in diameter (inches) for typical windbreak tree species in the North East region.

Tree Species	Ecoregions		
	211	221	222
Ulmus americana	0.19±0.001[a]	0.15±0.01[b]	0.19±0.01[a]
Abies balsamea	0.15±0.001[a]	0.097±0.009[b]	NA
Populus deltoides	0.08±0.02[a]	0.08±0.01[a]	0.09±0.01[a]
Juniperus virginiana	0.07±0.02[a]	0.08±0.008[a]	0.09±0.01[a]
Fraxinus pennsylvanica	0.17±0.01[a]	0.12±0.01[b]	0.14±0.001[b]
Celtis occidentalis	0.37±0.10[a]	0.04±0.05[b]	NA
Pinus strobus	0.20±0.002[a]	0.15±0.003[b]	0.14±0.006[b]
Picea abies	0.16±0.005[ab]	0.18±0.01[a]	0.12±0.024[b]
Pinus sylvestris	0.13±0.01[b]	0.15±0.03[ab]	0.18±0.01[a]
Quercus alba	0.08±0.00[c]	0.10±0.001[b]	0.17±0.02[a]
Quercus macrocarpa	0.15±0.00[a]	0.13±0.02[a]	0.13±0.02[a]
Quercus rubra	0.16±0.00[b]	0.17±0.00[b]	0.20±0.01[a]

Means with the same letter are not significantly different
NA = Not available

Table C-2.9. Mean annual increment in diameter (inches) for typical windbreak tree species in the Northern Plains region.

Tree Species	Ecoregions					
	223	251	255	331	332	334
Ulmus americana	0.18 ± 0.10^{ab}	0.19 ± 0.01^{ab}	0.14 ± 0.03^{ab}	0.11 ± 0.04^{abc}	0.25 ± 0.02^{abd}	0.02 ± 0.14^{abcd}
Populus deltoides	NA	0.31 ± 0.04^{a}	0.37 ± 0.11^{a}	0.15 ± 0.03^{a}	0.25 ± 0.02^{a}	NA
Juniperus virginiana	NA	0.17 ± 0.001^{a}	0.18 ± 0.04^{a}	0.16 ± 0.02^{a}	0.17 ± 0.01^{a}	NA
Fraxinus pennsylvanica	NA	0.16 ± 0.01^{a}	0.15 ± 0.01^{ab}	0.09 ± 0.01^{b}	0.13 ± 0.01^{b}	0.08 ± 0.02^{b}
Celtis occidentalis	0.11 ± 0.06^{a}	0.173 ± 0.01^{a}	0.17 ± 0.02^{a}	0.096 ± 0.12^{a}	0.19 ± 0.01^{a}	NA
Pinus ponderosa	NA	0.24 ± 0.14^{a}	NA	0.19 ± 0.03^{a}	0.22 ± 0.04^{a}	0.25 ± 0.01^{a}
Quercus macrocarpa	NA	0.11 ± 0.00^{b}	0.27 ± 0.05^{a}	0.06 ± 0.00^{d}	0.08 ± 0.00^{c}	0.06 ± 0.00^{d}
Quercus rubra	NA	0.18 ± 0.01^{a}	0.13 ± 0.05^{a}	NA	NA	NA

Means with the same letter are not significantly different
NA = Not available

Table C-3.1. Carbon storage potential (kg) for windbreak tree species in the North Lake States region projected to 50 years.

Tree Species	Ecoregions 212 (kg C tree^{-1} 50 yr^{-1}) Mean	212 S.E.	222 Mean	222 SE	251 Mean	251 SE	Model Id.
Ulmus americana	128.3	7.4	236.7	9.1	462.1	65.1	181
	41.9	0.8	27.4	6.8	NA	NA	75
	43.1	0.8	28.5	6.8	NA	NA	177
	35.5	0.7	23.1	5.7	NA	NA	9
	41.5	0.7	27.9	6.4	NA	NA	52
	35.8	0.6	24.8	5.2	NA	NA	82
	57.4	1.0	37.9	9.1	NA	NA	181
Populus deltoides	166.3	32.6	173.3	19.5	121.2	47.7	3
	328.5	88.5	345.4	53.9	218.3	113.8	181
Juniperus virginiana	39.9	10.6	38.1	4.0	30.1	9.2	138
	33.2	8.9	31.7	3.3	25.0	7.7	181
Pinus strobus	115.0	4.7	160.8	6.7	383.0	346.4	177
	70.3	2.4	92.7	3.2	175.2	147.9	114
	124.6	5.0	173.0	7.1	403.1	362.6	181
Fraxinus pennysilvanica	41.3	1.7	75.7	3.7	74.5	8.5	181
Celtis occidentalis	72.7	52.1	273.7	32.1	69.2	33.4	180
	87.8	62.5	328.1	38.3	83.7	40.0	181
	63.8	42.3	213.6	22.4	62.0	27.1	181a
Picea abies	57.9	16.8	247.7	45.4	NA	NA	80
	43.9	14.1	219.9	44.7	NA	NA	181
Pinus sylvestris	175.5	30.2	134.6	24.6	63.6	43.3	179a
	201.5	36.3	152.5	29.2	70.3	49.3	179b
	189.6	35.5	141.9	28.3	64.2	46.1	181

NA = Not available

Table C-3.1. (con't)

Tree Species	Ecoregions						Model Id.
	212		222		251		
	kg C tree^{-1} 50 yr^{-1}						
	Mean	S.E.	Mean	SE	Mean	SE	
Quercus alba	24.9	0.2	25.0	2.8	NA	NA	102
	33.3	0.3	33.5	4.3	NA	NA	119
	34.9	0.3	35.1	4.5	NA	NA	119
	33.7	0.3	33.9	4.3	NA	NA	119
	29.9	0.2	29.9	2.8	NA	NA	174
	23.7	0.2	23.8	2.8	NA	NA	12462
	27.1	0.2	27.2	3.2	NA	NA	12466
	32.2	0.3	32.4	3.7	NA	NA	12693
	38.9	0.3	39.1	4.1	NA	NA	181
Quercus macrocarpa	28.7	1.4	28.6	0.4	NA	NA	12099
	39.0	2.1	39.0	0.6	NA	NA	181
Quercus rubra	133.5	6.7	208.4	1.4	NA	NA	119
	114.9	8.4	216.5	2.1	NA	NA	29
	87.0	6.6	169.3	1.8	NA	NA	102
	112.0	7.7	205.4	1.9	NA	NA	114
	89.6	6.9	176.8	1.9	NA	NA	12467
	113.7	7.9	210.7	2.0	NA	NA	181

NA= Not available

Table C-3.2. Carbon storage potential (kg) for field windbreak tree species in the Corn Belt region projected to 50 years.

Tree species	Ecoregions								Model Id
	221		222		223		251		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	102.2	14.8	171.8	20.1	88.0	13.5	266.4	52.2	181
Abies balsamea	3.6	3.2	NA	NA	NA	NA	NA	NA	75
	4.0	3.4	NA	NA	NA	NA	NA	NA	177
	3.1	2.7	NA	NA	NA	NA	NA	NA	9
	4.2	3.6	NA	NA	NA	NA	NA	NA	52
	4.3	3.5	NA	NA	NA	NA	NA	NA	82
	5.3	4.6	NA	NA	NA	NA	NA	NA	181
Populus deltoides	188.5	42.5	197.7	21.8	281.3	50.3	NA	NA	3
	392.2	121.0	414.8	63.3	681.0	167.7	NA	NA	181
Juniperus virginiana	26.2	12.1	47.0	8.6	31.0	0.7	145.9	16.2	138
	21.8	10.1	39.1	7.2	25.8	0.6	122.3	13.7	181
Pinus strobus	170.6	18.2	357.8	56.6	191.2	38.9	121.0	14.9	177
	97.3	8.6	179.1	23.4	106.6	18.0	73.2	7.4	114
	183.4	19.3	379.8	59.1	205.1	41.0	130.8	15.8	181
Fraxinus pennysilvanica	NA	NA	115.3	15.7	86.3	13.2	149.4	18.4	181
Celtis occidentalis	180.0	74.9	256.1	32.0	125.6	20.5	NA	NA	180
	216.1	89.5	307.2	38.2	151.2	24.5	NA	NA	181
	145.8	54.8	201.3	22.5	106.5	15.5	NA	NA	181a
Pinus taeda	37.1	11.4	NA	NA	NA	NA	NA	NA	110a
	842.6	519.0	NA	NA	NA	NA	NA	NA	110b
	40.1	12.2	NA	NA	NA	NA	NA	NA	181
Pinus sylvestris	87.2	11.3	49.4	16.3	16.7	4.5	NA	NA	179a
	96.7	13.2	53.4	18.5	17.1	4.8	NA	NA	179b

NA= Not available

Table C-3.2 (con't)

Tree species	Ecoregions								Model Id
	221		222		223		251		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
	88.4	12.5	47.8	17.1	14.6	4.3	NA	NA	181
Quercus alba	41.7	0.3	41.8	3.9	52.2	2.3	41.8	3.9	102
	59.7	0.5	59.9	6.4	77.1	3.8	59.9	6.4	119
	62.9	0.5	63.2	6.8	81.5	4.0	63.2	6.8	119
	60.5	0.5	60.7	6.5	78.2	3.8	60.7	6.5	119
	46.1	0.3	46.1	3.6	55.7	2.0	46.1	3.6	174
	40.3	0.3	40.4	3.9	50.9	2.3	40.4	3.9	12462
	46.1	0.3	46.2	4.5	58.2	2.6	46.2	4.5	12466
	54.7	0.4	54.8	5.3	69.0	3.1	54.8	5.3	12693
	63.1	0.4	63.3	5.6	78.0	3.2	63.3	5.6	181
Quercus macrocarpa	81.0	25.9	55.7	10.5	71.6	35.3	55.7	10.5	12099
	117.8	39.8	78.9	15.8	103.9	53.7	78.9	15.8	181
Quercus rubra	297.9	24.0	297.9	24.0	229.8	21.4	229.8	21.4	119
	355.5	38.9	355.5	38.9	248.7	32.2	248.7	32.2	29
	290.6	35.1	290.6	35.1	196.8	27.5	196.8	27.5	102
	335.8	37.0	335.8	37.0	235.4	30.0	235.4	30.0	114
	307.0	37.9	307.0	37.9	206.2	29.4	206.2	29.4	12467
	347.0	38.8	347.0	38.8	241.9	31.3	241.9	31.3	181

NA= Not available

Table C-3.3. Carbon storage potential (kg) for field windbreak tree species in the Southern Plains region projected to 50 years.

Tree species	Ecoregions								Model Id
	223		231		232		255		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	127.4	64.5	154.4	37.5	104.1	29.5	177.5	60.6	181
Populus deltoides	NA	NA	NA	NA	1,113.7	503.2	859.2	316.7	3
	NA	NA	NA	NA	4,846.0	2,861.1	3,314.6	1,630.6	181
Juniperus virginiana	55.6	1.9	114.9	1.4	517.4	130.1	145.4	1.6	138
	46.4	1.6	96.2	1.2	437.3	110.6	121.9	1.4	181
Fraxinus pennysilvanica	141.6	68.5	99.5	6.7	101.7	19.6	105.0	16.3	181
Celtis occidentalis	133.9	61.9	48.5	39.1	NA	NA	111.4	106.6	180
	161.1	74.0	58.7	47.0	NA	NA	133.9	127.8	181
	111.8	46.7	44.1	33.3	NA	NA	90.2	84.2	181a
Pinus taeda	NA	NA	51.4	0.7	30.6	0.5	34.5	2.2	110a
	NA	NA	49.6	0.6	30.8	0.5	34.4	2.0	110b
	NA	NA	55.4	0.8	33.1	0.6	37.3	2.3	181
Quercus alba	52.0	10.4	189.1	127.2	NA	NA	33.8	8.1	102
	77.1	17.5	349.5	255.6	NA	NA	47.2	12.9	119
	81.6	18.7	376.3	276.8	NA	NA	49.7	13.7	119
	78.2	17.8	355.9	260.7	NA	NA	47.8	13.0	119
	55.2	9.2	155.8	91.9	NA	NA	38.6	7.8	174
	50.7	10.4	194.4	133.7	NA	NA	32.5	8.1	12462
	58.0	11.9	221.8	152.5	NA	NA	37.2	9.2	12466
	68.7	14.1	261.2	179.0	NA	NA	44.2	10.9	12693
	77.5	14.4	254.2	163.0	NA	NA	51.9	11.7	181
Quercus macrocarpa	121.7	33.2	114.5	91.1	NA	NA	65.8	11.7	12099
	181.7	52.5	174.3	142.9	NA	NA	94.4	17.7	181

NA= Not available

Table C-3.3 (con't)

Tree species	Ecoregions								Model Id
	223		231		232		255		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Quercus falcata	78.3	39.5	136.2	19.9	NA	NA	112.2	109.2	10628
	99.7	51.2	175.0	26.1	NA	NA	145.6	142.1	10313
	103.6	52.4	180.4	26.4	NA	NA	148.8	145.0	8391
	111.8	54.8	191.5	27.0	NA	NA	155.3	150.6	181

NA= Not available

Table C-3.4. Carbon storage potential (kg) for field windbreak tree species in the Delta States region projected to 50 years.

Tree species	Ecoregions								Model Id
	223		231		232		234		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	65.2	22.2	134.3	17.4	250.5	163.1	152.4	18.7	181
Populus deltoides	NA	NA	287.0	100.5	NA	NA	NA	NA	3
	NA	NA	717.5	336.5	NA	NA	NA	NA	181
Juniperus virginiana	38.4	0.8	76.5	1.1	105.5	39.9	78.4	22.8	138
	31.9	0.6	63.9	1.0	88.3	33.6	65.5	19.1	181
Fraxinus pennysilvanica	44.5	18.2	86.3	13.2	109.6	58.2	149.4	18.4	181
Celtis occidentalis	109.1	37.0	75.7	29.3	NA	NA	74.8	30.9	180
	131.4	44.3	91.5	35.2	NA	NA	56.3	21.1	181
	93.6	28.5	67.5	23.5	NA	NA	56.3	21.1	181a
Pinus taeda	30.6	2.6	52.0	0.4	48.5	0.3	63.4	4.0	110a
	487.9	92.1	1,591.6	24.5	1,361.8	21.5	2,499.6	352.7	110b
	33.2	2.8	56.0	0.4	52.3	0.4	68.1	4.2	181
Quercus alba	44.1	18.2	51.5	4.5	125.4	35.9	129.5	127.1	102
	64.6	30.0	76.0	7.5	211.3	68.5	239.3	237.1	119
	68.3	32.0	80.4	8.0	225.8	73.9	257.6	255.4	119
	65.5	30.5	77.1	7.6	214.8	69.8	243.7	241.5	119
	47.7	16.7	54.9	4.0	114.6	27.5	106.2	102.0	174
	42.9	18.3	50.1	4.5	126.2	37.3	133.2	131.1	12462
	49.0	20.9	57.3	5.1	144.1	42.6	151.9	149.6	12466
	58.1	24.7	68.0	6.1	170.1	50.0	178.9	176.1	12693
	66.2	25.7	76.8	6.3	176.0	47.2	173.8	169.5	181
Quercus rubra	122.7	8.8	128.0	16.4	136.3	114.9	111.8	29.7	119
	103.4	4.5	104.5	19.7	143.6	137.3	87.6	34.1	29

NA= Not available

Table C-3.4. (con't)

Tree species	Ecoregions: 223 (kg C tree^{-1} 50 yr^{-1})		231		232		234		Model Id
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Quercus falcata	77.9	3.4	78.8	15.2	114.6	109.6	66.0	26.1	102
	102.0	4.1	102.9	18.1	136.9	128.5	87.0	31.5	114
	79.8	3.6	80.8	15.9	120.2	115.4	67.6	27.3	12467
	103.3	4.3	104.3	18.6	140.7	132.5	88.1	32.4	181
	80.2	14.4	112.3	17.7	114.9	35.5	131.0	19.5	10628
	102.1	18.7	143.9	23.2	147.4	46.5	168.3	25.6	10313
	106.1	19.1	148.8	23.6	152.2	47.2	173.5	25.9	8391
	114.6	19.9	158.7	24.2	162.1	48.5	184.1	26.5	181

NA= Not available

Table C-3.5. Carbon storage potential (kg) for a field windbreak tree species in the Appalachia region projected to 50 years.

Tree species	Ecoregions								Model Id
	221		223		231		234		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	65.2	22.2	52.9	9.9	88.3	16.2	97.3	54.3	181
Populus deltoides	715.1	506.9	319.1	143.2	420.7	89.1	863.8	200.1	3
	910.8	238.6	849.6	498.1	1,004.5	347.8	1,825.6	555.9	181
Juniperus virginiana	38.4	0.8	38.4	0.8	38.8	7.8	NA	NA	138
	31.9	0.6	31.9	0.6	32.3	6.5	NA	NA	181
Pinus strobus	106.6	13.8	61.4	44.7	274.8	274.7	NA	NA	177
	66.0	7.1	40.1	25.7	127.9	127.8	NA	NA	114
	115.6	14.7	67.0	48.1	289.8	289.6	NA	NA	181
Fraxinus pennysilvanica	53.6	19.5	51.9	9.7	149.4	18.4	324.7	114.7	181
Celtis occidentalis	147.2	22.7	47.2	11.1	374.6	119.7	36.9	9.5	180
	177.0	27.1	57.3	13.4	448.4	142.7	44.8	11.5	181
	122.7	16.9	44.6	9.4	281.5	80.9	35.8	8.2	181a
Pinus taeda	49.9	3.3	60.4	3.7	35.0	2.7	NA	NA	110a
	1,674.1	248.6	2,573.7	353.9	752.1	128.8	NA	NA	110b
	53.7	3.5	64.8	3.9	37.8	2.9	NA	NA	181
Quercus alba	41.7	0.2	52.3	4.5	78.9	14.6	NA	NA	102
	59.7	0.3	77.3	7.6	123.3	25.8	NA	NA	119
	62.9	0.3	81.7	8.1	131.0	27.6	NA	NA	119
	60.5	0.3	78.4	7.7	125.2	26.2	NA	NA	119
	46.1	0.2	55.8	4.1	78.6	12.3	NA	NA	174
	40.3	0.2	51.0	4.5	77.9	14.9	NA	NA	12462
	46.1	0.2	58.3	5.2	89.0	17.0	NA	NA	12466
	54.7	0.3	69.1	6.1	105.4	20.0	NA	NA	12693

NA= Not available

Table C-3.5. (con't)

Tree species	Ecoregions								Model Id
	221		223		231		234		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
	63.1	0.3	78.1	6.3	114.6	19.9	NA	NA	181
Quercus rubra	151.3	17.8	208.8	20.5	152.7	35.6	312.6	143.5	119
Quercus rubra	137.9	23.2	217.6	30.0	141.3	46.4	393.3	232.2	29
	105.3	18.5	170.5	25.1	108.4	37.0	337.4	213.6	102
	133.1	21.3	206.6	27.7	136.2	42.7	378.0	223.6	114
	108.9	19.5	178.1	26.7	112.3	39.1	359.4	231.0	12467
	135.6	22.0	211.8	28.9	138.9	44.1	392.5	234.9	181
Quercus falcata	53.8	0.1	44.0	9.9	95.4	16.0	NA	NA	10628
	67.9	0.1	55.2	12.6	121.9	20.9	NA	NA	10313
	71.1	0.1	58.0	13.1	126.3	21.3	NA	NA	8391
	77.9	0.2	64.0	13.9	135.6	22.0	NA	NA	181

NA= Not available

Table C-3.6. Carbon storage potential (kg) for a field windbreak tree species in the Rocky Mountain North region projected to 50 years.

Tree species	Ecoregions								Model Id
	331		332		333		342		
	kg C tree^{-1} 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Ponderosa pine	159.6	0.5	155.2	0.5	146.4	14.0	130.0	14.0	181
	164.2	3.7	164.2	3.7	154.5	6.8	136.3	6.8	1000
	158.9	3.7	152.5	3.7	143.6	6.8	128.1	6.4	2000
Pinus Contorta	666.6	784.0	912.9	1,053.5	181.6	2,892.7	666.6	1,206.1	181
Fraxinus pennysilvanica	219.8	119.7	NA	NA	NA	N A	NA	NA	181

NA= Not available

Table C-3.7. Carbon storage potential (kg) for a field windbreak tree species in the Rocky Mountain South region projected to 50 years.

Tree species	Ecoregions								Model Id
	313		321		331		341		
	kg C $tree^{-1}$ 50 yr^{-1}								
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Ponderosa pine	208.4	0.5	NA	NA	246.3	2.6	NA	NA	181
	216.0	3.7	NA	NA	262.7	0.2	NA	NA	1000
	217.9	3.7	NA	NA	264.9	0.2	NA	NA	2000

NA= Not available

Table C-3.8. Carbon storage potential (kg) for a field windbreak tree species in the North East region projected to 50 years.

Tree species	Ecoregions 211		221		222		Model Id
	kg C tree^{-1} 50 yr^{-1}						
	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	127.0	10.3	74.7	6.4	149.8	14.0	181
Abies balsamea	64.7	1.0	22.7	5.0	NA	NA	75
	65.7	1.0	23.8	5.1	NA	NA	177
	54.9	0.9	19.1	4.2	NA	NA	9
	62.1	0.9	23.5	4.8	NA	NA	52
	51.7	0.7	21.2	4.0	NA	NA	82
	87.6	1.3	31.6	6.8	NA	NA	181
Populus deltoides	20.2	8.3	19.6	4.2	23.9	4.5	3
	18.3	9.8	17.0	4.9	22.4	5.8	181
Juniperus virginiana	16.3	8.2	18.4	3.4	24.8	4.1	138
	13.5	6.8	15.2	2.8	20.5	3.4	181
Pinus strobus	122.8	3.1	68.5	3.1	59.1	9.3	177
	74.2	1.5	45.8	1.7	40.5	5.3	114
	132.8	3.3	74.9	3.4	64.7	10.0	181
Fraxinus pennysilvanica	93.5	12.0	42.4	5.8	70.8	6.0	181
Celtis occidentalis	1,240.1	515.5	13.7	13.6	204.9	30.0	180
	1,478.5	613.1	16.8	16.6	246.0	35.9	181
	338.4	31.1	13.9	13.6	164.9	21.6	181a
Picea abies	105.7	7.8	145.7	22.8	60.7	24.3	80
	85.2	6.9	122.0	21.1	46.5	20.4	181
Pinus sylvestris	50.0	6.3	69.3	29.2	97.0	15.4	179a
	53.9	7.1	76.3	33.6	108.1	17.9	179b
	48.2	6.6	69.4	31.5	99.2	17.1	181

NA= Not available

Table C-3.8. (con't)

Tree species	Ecoregions 211		221		222		Model Id
	kg C tree^{-1} 50 yr^{-1}						
	Mean	SE	Mean	SE	Mean	SE	
Quercus alba	13.2	0.1	24.9	0.7	114.5	36.5	102
	16.3	0.2	33.3	1.1	189.2	67.7	119
	17.0	0.2	34.9	1.1	201.8	72.8	119
	16.5	0.2	33.7	1.1	192.2	68.9	119
	17.5	0.2	29.9	0.7	107.0	28.9	174
	12.3	0.1	23.7	0.7	114.6	37.6	12462
	14.1	0.2	27.1	0.8	130.9	42.9	12466
	16.8	0.2	32.2	0.9	154.7	50.5	12693
	21.6	0.2	39.0	1.0	162.1	48.5	181
Quercus macrocarpa	78.5	0.3	57.4	21.1	57.4	21.1	12099
	113.6	0.4	81.9	31.7	81.9	31.7	181
Quercus rubra	150.8	1.8	169.1	1.9	229.8	21.4	119
	136.8	2.3	161.1	2.5	248.7	32.2	29
	104.3	1.8	123.8	2.1	196.8	27.5	102
	132.1	2.1	154.4	2.3	235.4	30.0	114
	288.9	34.2	292.1	34.5	206.2	29.4	12467
	134.5	2.2	157.6	2.4	241.9	31.3	181

NA= Not available

Table C-3.9. Carbon storage potential (kg) for a field windbreak tree species in the Northern Plains region projected to 50 years.

Tree species	Ecoregions						Model Id
	223		251		255		
	kg C tree^{-1} 50 yr^{-1}						
	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	117.6	16.5	134.3	17.4	68.1	33.4	181
Populus deltoides	NA	NA	199.2	43.5	281.4	135.4	114
	NA	NA	423.2	126.6	718.8	447.7	12467
Juniperus virginiana	NA	NA	114.0	7.3	127.9	58.9	181
	NA	NA	95.5	6.1	107.3	49.6	181
Fraxinus pennysilvanica	NA	NA	85.9	7.6	78.0	22.4	181
Celtis occidentalis	75.9	70.1	154.1	23.3	150.4	45.4	180
	91.5	84.2	185.3	27.9	180.9	54.3	181
	64.6	57.5	127.9	17.3	124.8	33.8	181a
Ponderosa pine	NA	NA	128.6	74.4	NA	NA	181
	NA	NA	133.5	82.5	NA	NA	1000
	NA	NA	128.7	79.4	NA	NA	2000
Quercus macrocarpa	NA	NA	36.3	0.8	349.1	148.0	12099
	NA	NA	50.1	1.2	557.5	249.3	181
Quercus rubra	NA	NA	188.7	19.7	114.2	74.1	119
	NA	NA	188.8	27.7	103.4	84.2	29
	NA	NA	146.6	22.8	79.9	65.5	102
	NA	NA	179.9	25.5	100.3	78.5	114
	NA	NA	152.6	24.2	82.8	68.5	12467
	NA	NA	184.1	26.5	102.3	80.7	181

NA= Not available

Table C-3.9. (con't)

Tree species	Ecoregions						Model Id
	331		332		334		
	kg C tree^{-1} 50 yr^{-1}						
	Mean	SE	Mean	SE	Mean	SE	
Ulmus americana	43.0	31.5	272.7	33.3	67.3	32.6	181
Populus deltoides	58.9	19.5	137.2	21.1	NA	NA	114
	79.3	35.2	250.3	53.1	NA	NA	12467
Juniperus virginiana	88.2	23.5	107.5	7.7	NA	NA	181
	73.7	19.8	90.0	6.5	NA	NA	181
Fraxinus pennysilvanica	23.0	5.2	48.6	5.3	18.7	12.5	181
Celtis occidentalis	33.2	8.9	197.0	27.2	NA	NA	180
	40.4	10.7	236.5	32.4	NA	NA	181
	32.6	7.8	159.2	19.6	NA	NA	181a
Ponderosa pine	59.7	58.3	83.3	80.6	NA	NA	181
	60.3	58.9	87.0	87.0	NA	NA	1000
	58.1	56.7	84.4	84.3	NA	NA	2000
Quercus macrocarpa	8.0	NA	16.4	0.1	NA	NA	12099
	10.1	NA	21.6	0.1	NA	NA	181

NA= Not available

Table C-4.1. Carbon storage potential from field windbreak tree species in the ecoregions within the North Lake States region, projected to 50 years.

Tree Species	Ecoregions					
	212		222		251	
	Mg C ha^{-1} 50 yr^{-1}					
	Mean[1]	SE	Mean	SE	Mean	SE
Ulmus americana	104.4	6.0	192.7	7.4	376.1	53.0
Abies balsamea	63.8	1.2	42.1	10.1	NA	NA
Populus deltoides	267.4	72.0	281.2	43.9	177.7	92.6
Juniperus virginiana	83.9	22.4	80.0	8.4	63.1	19.3
Pinus strobus	138.4	5.5	192.2	7.9	447.8	402.8
Fraxinus pennysilvanica	33.6	1.4	61.6	3.0	60.6	6.9
Celtis occidentalis	71.4	50.9	267.1	31.1	68.1	32.6
Picea abies	48.8	15.7	244.3	49.6	NA	NA
Pinus sylvestris	210.7	39.4	157.7	31.4	71.3	51.2
Quercus alba	31.7	0.3	31.8	3.4	NA	NA
Quercus macrocarpa	31.7	1.7	31.7	0.5	NA	NA
Quercus rubra	92.6	6.5	171.5	1.6	NA	NA

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-4.2. Carbon storage potential from field windbreak tree species in the ecoregions within the Corn Belt region, projected to 50 years.

Tree species	Ecoregions							
	221		222		223		251	
	Mg C ha^{-1} 50 yr^{-1}							
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus americana	83.2	12.0	139.9	16.4	71.7	11.0	216.9	42.5
Abies balsamea	5.9	5.1	NA	NA	NA	NA	NA	NA
Populus deltoides	319.2	98.5	337.6	51.5	554.3	136.5	NA	NA
Juniperus virginiana	55.0	25.6	98.8	18.3	65.1	1.5	308.9	34.6
Pinus strobus	203.7	21.4	421.9	65.6	227.8	45.5	145.3	17.5
Fraxinus pennysilvanica	NA	NA	93.8	12.8	70.3	10.8	121.6	15.0
Celtis occidentalis	175.9	72.9	250.0	31.1	123.0	20.0	NA	NA
NPinus taeda	44.5	13.6	NA	NA	NA	NA	NA	NA
Pinus sylvestris	98.2	13.9	53.1	19.0	16.3	4.8	NA	NA
Quercus alba	51.4	0.3	51.5	4.5	63.5	2.6	51.5	4.5
Quercus macrocarpa	95.9	32.4	64.2	12.9	84.6	43.7	64.2	12.9
Quercus rubra	282.4	31.6	282.4	31.6	196.9	25.4	196.9	25.4

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-4.3. Carbon storage potential from field windbreak tree species in the ecoregions within the Southern Plains region, projected to 50 years.

Tree species	Ecoregions							
	223		231		232		255	
	Mg C ha^{-1} 50 yr^{-1}							
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus Americana	103.7	52.5	125.7	30.5	84.7	24.0	144.5	49.3
Populus deltoides	NA	NA	NA	NA	3,944.7	2,328.9	2,698.1	1,327.3
Juniperus virginiana	117.1	4.0	242.9	3.0	1,104.2	279.3	307.8	3.5
Fraxinus pennysilvanica	115.2	55.7	81.0	5.5	82.8	16.0	85.5	13.3
Celtis occidentalis	131.2	60.3	47.8	38.3	NA	NA	109.0	104.0
Pinus taeda	NA	NA	61.5	0.8	36.8	0.6	41.4	2.6
Quercus alba	63.1	11.7	206.9	132.7	NA	NA	42.2	9.5
Quercus macrocarpa	147.9	42.7	141.9	116.4	NA	NA	76.8	14.4
Quercus falcata	91.0	44.6	155.9	22.0	NA	NA	126.4	122.6

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-4.4. Carbon storage potential from field windbreak tree species in the ecoregions within the Delta States region, projected to 50 years.

Tree species	Ecoregions							
	223		231		232		234	
	Mg C ha^{-1} 50 yr^{-1}							
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus americana	53.1	18.1	109.3	14.1	203.9	132.7	124.0	15.3
Populus deltoides	NA	NA	584.1	273.9	NA	NA	NA	NA
Juniperus virginiana	80.6	1.6	161.4	2.4	223.0	84.8	165.4	48.3
Fraxinus pennysilvanica	36.3	14.8	70.3	10.8	89.2	47.4	121.6	15.0
Celtis occidentalis	107.0	36.1	74.5	28.6	NA	NA	45.8	17.2
Pinus taeda	36.9	3.1	62.2	0.4	58.1	0.4	75.6	4.7
Quercus alba	53.9	20.9	62.5	5.1	143.2	38.4	141.5	138.0
Quercus rubra	84.1	3.5	84.9	15.2	114.5	107.9	71.7	26.3
Quercus falcata	93.3	16.2	129.2	19.7	132.0	39.5	149.9	21.6

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-4.5. Carbon storage potential from field windbreak tree species in the ecoregions within the Appalachia region projected to 50 years.

Tree species	Ecoregions							
	221		223		231		234	
	Mg C ha^{-1} 50 yr^{-1}							
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus americana	53.1	18.1	43.1	8.1	71.9	13.2	79.2	44.2
Populus deltoides	741.4	194.2	691.6	405.4	817.6	283.1	1,486.0	452.5
Juniperus virginiana	80.6	1.6	80.6	1.6	81.5	16.4	0.0	0.0
Pinus strobus	128.4	16.3	74.4	53.4	321.9	321.8	0.0	0.0
Fraxinus pennysilvanica	43.6	15.9	42.3	7.9	121.6	15.0	264.3	93.4
Celtis occidentalis	144.1	22.0	46.6	10.9	365.0	116.1	36.5	9.3
Pinus taeda	59.6	3.9	72.0	4.4	41.9	3.2	NA	NA
Quercus alba	51.4	0.2	63.6	5.1	93.3	16.2	NA	NA
Quercus rubra	110.4	17.9	172.4	23.5	113.0	35.9	319.5	191.2
Quercus falcata	63.4	0.1	52.1	11.3	110.4	17.9	NA	NA

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-4.6. Carbon storage potential from field windbreak tree species in the ecoregions within the Rocky Mountain North region projected to 50 years.

Tree species	Ecoregions							
	331		332		333		342	
	Mg C ha^{-1} 50 yr^{-1}							
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ponderosa pine	177.4	0.5	172.4	0.5	162.6	15.5	144.4	15.5
Pinus contorta	740.5	71.1	1,014.3	181	201.8	21	740.5	134
Fraxinus pennysilvanica	178.9	97.4	NA	NA	NA	NA	NA	NA

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-6.7. Carbon storage potential from field windbreak tree species in the ecoregions within the North East region projected to 50 years.

Tree species	Ecoregions					
	211		221		222	
	Mg C ha^{-1} 50 yr^{-1}					
	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus americana	103.4	8.4	60.8	5.2	122.0	11.4
Abies balsamea	97.3	1.5	35.1	7.5	NA	NA
Populus deltoides	14.9	8.0	13.9	4.0	18.2	4.7
Juniperus virginiana	34.1	17.2	38.4	7.1	51.9	8.5
Pinus strobus	147.6	3.7	83.2	3.7	71.9	11.1
Fraxinus pennysilvanica	76.1	9.7	34.5	4.7	57.6	4.8
Celtis occidentalis	1,203.5	499.0	13.7	13.5	200.2	29.2
Picea abies	275.4	25.3	11.3	11.1	134.2	17.6
Pinus sylvestris	94.7	7.7	135.5	23.5	51.7	22.7
Quercus alba	53.5	7.3	77.1	35.0	110.3	19.0
Quercus macrocarpa	17.5	0.2	31.7	0.8	132.0	39.5
Quercus rubra	92.4	0.3	66.6	25.8	66.6	25.8

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-6.8. Carbon storage potential from field windbreak tree species in the ecoregions within the Northern Plains region projected to 50 years.

Tree species	Ecoregions					
	223		251		255	
	Mg C ha^{-1} 50 yr^{-1}					
	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus americana	95.7	13.4	109.3	14.1	55.4	27.2
Populus deltoides	NA	NA	344.5	103.1	585.1	364.4
Juniperus virginiana	NA	NA	288.0	18.3	323.0	148.7
Fraxinus pennysilvanica	NA	NA	69.9	6.2	63.5	18.2
Celtis occidentalis	74.5	68.5	150.8	22.7	147.2	44.2
Ponderosa pine	NA	NA	142.9	82.7	NA	NA
Quercus macrocarpa	NA	NA	40.8	1.0	453.8	202.9
Quercus rubra	NA	NA	149.9	21.6	83.2	65.7

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

Table C-6.8. (con't)

Tree species	Ecoregions					
	331		332		334	
	Mg C ha^{-1} 50 yr^{-1}					
	Mean	S.E.	Mean	S.E.	Mean	S.E.
Ulmus americana	35.0	25.7	222.0	27.1	54.8	26.5
Populus deltoides	64.6	28.7	203.7	43.2	NA	NA
Juniperus virginiana	222.6	59.4	271.5	19.4	NA	NA
Fraxinus pennysilvanica	18.7	4.2	39.6	4.3	NA	NA
Celtis occidentalis	32.9	8.7	192.5	26.4	NA	NA
Ponderosa pine	66.3	64.8	92.5	89.6	NA	NA

NA= Not available

[1] Mean carbon storage potential per ecoregion using Jenkins coefficients and IPCC conversion factors: 0.48 for deciduous and 0.51 for conifers (Lamlom and Sevidge 2003). Tree density calculated in 814; 1,111 and 2,525 hardwood, conifers and small conifers trees per ha, respectively.

APPENDIX D. CARBON STORAGE POTENTIAL FOR WINDBREAK DESIGNS.

Table D-1. Tree distribution in field windbreaks and cropping area occupied by different field windbreak designs.

Field Windbreak Design	Tree distance (m)		Width	Area	Area taken out from a hectare of cropland	
	Within[1]	Between	m	sq. m	sq. m	(%)
One row small shrub[3]	1.2	-	1.2	120.0[2]	200	1.5
One row small coniferous	2.0	-	2.0	200.0	250	2.5
One row tall deciduous	3.5	-	3.5	350.0	233	3.0
One row tall coniferous	3.0	-	3.0	300.0	200	2.0
Two rows tall deciduous	3.5	6.0	9.6	960.1	640	6.4
Two rows tall coniferous	3.0	6.0	9.1	914.4	609	6.1
One row tall coniferous and one row tall deciduous	3.5x3.0	6.0	9.4	939.0	629.1	6.3
One row tall coniferous and one row shrubs	3.0x1.2	6.0	8.2	824.0	552.1	5.5
One row tall deciduous and one row shrubs	3.5x1.2	6.0	8.5	847.0	567.5	5.7
One row tall coniferous and one row small coniferous	3.0x2.0	6.0	8.6	863.0	578.2	5.8
One row tall deciduous and one row small coniferous	3.5x2.0	6.0	8.9	886.0	593.6	5.9
Three rows tall coniferous	3.0x3.0x3.0	6.0	15.3	1,530	1,025.1	10.3
Three row tall deciduous	3.5x3.5x3.5	6.0	15.7	1,570	1,051.9	10.5
Two rows tall deciduous and one row tall coniferous	3.0x3.0x3.5	6.0	15.5	1,549	1,037.8	10.4
One row tall deciduous, one row tall conifers and one row shrubs	3.5x3.0x1.2	6.0	14.3	1,434	960.8	9.6
One row tall deciduous, one row tall coniferous and one row small coniferous	3.5x3.0x2.0	6.0	15.0	1,496	1,002.3	10.0

[1] Source: USDA NRCS Code 380. [2] Assuming a spatial configuration where the windbreak width is formed by the distance between rows and a half of the distance within trees. The average windbreak height was 25 ft. (7.6 m.) for tall coniferous and deciduous trees. For shrubs and small coniferous, windbreak height was stablished in 10 and 14 ft. (3 and 4 m.), respectively. The protected area by the windbreaks was 20H (152 m.).[3] windbreaks made of shrubs (3 m. height) give full protection to 3 ha of crops.

APPENDIX E. IMPACT OF WINDBREAKS ON THE C EMISSIONS FOR DIFFERENT CROPPING SYSTEMS.

Table E-1. Crop systems in different regions and states of the continental United States.

Region	State	Crop	Id[1]	System Description
NLS	WI	Corn	1	Continuous corn, 155 bu.
		Corn	2	Corn after soybean, 181 bu.
		Soybean	3	Soybean after corn, 55 bu.
		Wheat	4	No description
CB	OH	Corn	5	Conservation Tillage (No till)
		Corn	6	Conservation Tillage (No till)
		Corn	7	Conservation Tillage (No till)
		Soybean	8	Conservation Tillage Corn/No-Till RR[1] Soybean
		Soybean	9	Conservation Tillage Corn/No-Till RR Soybean
		Soybean	10	Conservation Tillage Corn/No-Till RR Soybean
		Wheat	11	Wheat/Corn/No-Till RR Soybeans
		Wheat	12	Wheat/Corn/No-Till RR Soybeans
		Wheat	13	Wheat/Corn/No-Till RR Soybeans
	IO	Corn	14	Corn following Corn
		Corn	15	Corn following Corn
		Corn	16	Corn following Corn

[1] Identifier for each crop system used in the following tables

Table E-1. (con't)

Region	State	Crop	Id[1]	System Description
		Soybean	17	Herbicide Tolerant Soybeans following Corn (no irrigated)
		Soybean	18	Herbicide Tolerant Soybeans following Corn
		Soybean	19	Herbicide Tolerant Soybeans following Corn
SP	TX	Corn	20	Corn - GMO Seed, Conventional Till-12 Row, Dryland
		Corn	21	Corn for grain, Bt[2] Furrow irrigated
		Soybean	22	Soybeans, RR[3], Furrow Irrigated, Following Corn or Sorghum
		Soybean	23	Soybeans, Roundup Ready, Sprinkler Irrigated
		Wheat	24	Continuous Wheat, Furrow Irrigated
		Wheat	25	Continuous Wheat, Sprinkler Irrigated
DS	AR	Corn	26	Stacked gene, Center Pivot Irrigation
		Corn	27	Stacked gene, No Irrigation
		Soybean	28	RR, Furrow Irrigation
		Soybean	29	RR, Center Pivot Irrigation
		Soybean	30	RR, no Irrigation
		Wheat	31	Table 28-A. Wheat enterprise
AP	TE	Corn	32	Non-Irrigated Corn, No-Till
		Corn	33	Non-Irrigated Corn, Conventional Tillage
		Corn	34	Corn, No-Till, Irrigated, 225 Bushels/Acre Yield

[2] *Bacillus thuringiensis*
[3] Roundup ready crops (RR): Crops genetically modified to be resistant to the herbicide Roundup (Monsanto 2014).

Table E-1. (con't)

Region	State	Crop	Id[1]	System Description
		Soybean	35	Non-Irrigated Soybean Budget (No-Till)
		Soybean	36	Irrigated Soybean Budget (No-Till)
		Wheat	37	Wheat Budget (Conventional Tillage)
RMN	IO	Wheat	38	2013 Eastern Idaho Dryland Hard Red Winter Wheat Following Summer Fallow
		Wheat	39	Table 1. 2013 Eastern Idaho Dryland Hard White Spring Wheat: Higher Rainfall Areas.
		Wheat	40	Table 1. 2013 Irrigated Soft White Winter Wheat for Eastern Idaho.
		Potato[4]	41	Table 1. 2013 Irrigated Russet Burbank Commercial Potatoes With Fumigation and On-Farm Storage for Eastern Idaho: Bannock, Bingham and Power Counties.
		Potato	42	Table 1. 2013 Irrigated Russet Burbank Commercial Potatoes With On-Farm Storage for Eastern Idaho Northern Region: Bonneville and Madison Counties.
		Corn	43	Continuous corn
RMS	CO	Corn	44	Table 16. 2013. dryland Corn in North East Colorado, Reduced till in a two -crop in three year Rotation
		Corn	45	Table 5. 2013. Irrigated Corn
		Wheat	46	Table 15. 2013 Estimated Production Costs and Returns - Dryland Winter Wheat in Northeastern Colorado. Reduced-Till in a Two-Crop in Three-Year Rotation
		Wheat	47	Table 14. 2013. dryland Winter Wheat in Northeastern Colorado , conventional tillage-Till Wheat - Fallow Rotation

[4] Potato units are given in cwt which stands for "centum weight," which is another term for "hundredweight."

Table E-1. (con't)

Region	State	Crop	Id	System Description
		Potato	48	Table 6. 2013 Estimated Production Costs and Returns - Irrigated Potatoes in Northeastern Colorado (550 cwt)
NE	MA	Potato	49	no Irrigation
NP	NE	Corn	50	15. Corn, conventional tillage, continuous, 90 bu yield goal (85 bu, actual yield
		Corn	51	22. Corn, Continuous, SmartStax[5] RIB Complete, 190 bu yield goal (180 bu, actual yield), canal irrigated, gravity, 15 acre-inches
		Corn	52	24. Corn, no-till, SmartStax, RIB Complete[6], continuous, 250 bu yield goal (235 bu, actual yield), pivot irrigated, 800 GPM 35 PSI, 9 acre-inches
		Wheat	53	65. Wheat, no-till after beans, 100 bu, yield Goal (90 bu actual yield)/Pivot irrigated, 800 GPM 35 PSI, 8 acre-inches
		Wheat	54	63.Wheat, Clean Till Fallow, 1 Crop in 2 yr, 50 bu yield goal (45 bu actual yield)/dryland
		Wheat	55	65. Wheat, no-till wheat before corn, 2 crops in 3 yr, 65 bu yield goal (60 bu actual yield) dryland
		Soybean	56	48. Soybeans, tilled seedbed, Roundup Ready® after corn (62 bu actual yield)/pivot irrigated, 800 GPM 35 PSI, 9 acre-inches

[5] SmartStax: Brand of genetically modified seed. Includes eight genes artificially added to a plant. The traits include protection and herbicide tolerance (Bendbrook 2009).
[6]SmartStax RIB complete: all appropriate amount of Refuge seed as farmer need for a field in the Corn Belt has already been blended into the bag with Bt seed (Monsanto 2014).

Table E-1. (con't)

Region	State	Crop	Id1	System Description
		Soybean	57	47. Soybeans, no-till, Roundup Ready continuous (39 bu actual yield)/ dryland
		Soybean	58	51. Soybeans Roundup Ready, no-till narrow row, continuous (59 bu actual yield)/pivot irrigated, 800 GPM 35 PSI, 6 acre-inches

Table E-2. Carbon equivalent emissions for corn systems in the United States.

Region	State	Id[1]	Bu[2]	Carbon equivalent emissions (kg CE ha^{-1} yr^{-1})								
				Fuel [3]	Fertilizers[4]	Lime	Seed[5]	Pesticides[6]	T. inputs[7]	Drying[8]	C. residue[9]	Total
NLS	WI	1	383	69	217	-	19	11	2	35	107	459.9[10]
		2	447	69	159	-	22	8	2	40	123	423.6
CB	OH	5	316	48	170	24	16	15	5	29	90	396.4
		6	395	48	210	24	19	15	5	36	110	467.3
		7	474	48	249	24	23	15	6	43	131	539.2
	IA	14	358	38	242	-	18	16	2	32	101	447.9
		15	408	69	243	-	20	16	2	37	114	499.8
		16	457	69	244	-	23	16	2	41	126	520.7
SP	TX	20	247	49	77	-	12	16	1	22	72	248.6
		21	494	269	322	-	24	17	2	45	136	814.8
DS	AR	26	445	66	292	-	22	13	3	40	123	558.0
		27	309	66	208	-	15	13	2	28	88	419.2
AP	TN	32	371	61	225	44	18	10	8	34	104	503.8

[1]Crop system identifier for more information the reader is refers to Table E-1.

[2]Crop yields from crop budgets (2014), these budgets were transformed to bushels ha (1 ha = 2.47 acres)

[3]Calculated based on diesel fuel. This fuel has an emission factor of 10,180 g CO_2 per gallon and 2.77 kg C gal^{-1} (Federal Register 2010).

[4]Encompass carbon emissions from production, transportation, storage and distribution of agricultural chemicals: nitrogen (urea), triple super phosphate (P_2O_5) and potassium sulphate (K_2O). Likewise, N_2O transfer from synthetic fertilizer (IPCC 2013).

[5] Carbon emissions calculated based on the kg per ha with a moisture less than 12% for corn, soybean and winter wheat and 90% for potatoes.

[6] Calculations were based on active ingredients of the herbicides, insecticides and fungicides.

[7] Transport of all inputs from distribution centers and trucking based on 900 bushels loads, 6 mpg, oil and lube 10% of the fuel cost.

[8] Drying cost based on 2.5% of the moisture removed (0.02 gal of LP per percent of point of moisture removed) (Ohio State 2014), Crop moisture at harvest (20%) and crop moisture at storage (15%) (Beuerlein 2008).

[9] Crop residue based on the amount of carbon released by the plant material remaining after harvesting, including leaves, stalks, and roots.

[10] In this point we are in the Northern Lake States under continuous corn, not irrigated, source: http://www.uwex.edu/ces/farmteam/budgets/fieldcrop.cfm (verified 03/26/2015). We use 8.2 gal of diesel fuel emitting 22.9 kg CE per acre, 166 kg N, 59.8 kg K_2O and 39kg P_2O_5, 2 pints of Harnes, 4 ounces of Hornet WDG /acre. This crop system emits 459.9 kg CE per hectare.

Table E-2 (con't)

Region	State	Id[1]	Bu[2]	Carbon equivalent emissions (kg CE ha-1 yr-1)								
				Fuel [3]	Fertilizers[4]	Lime	Seed[5]	Pesticides[6]	T. inputs[7]	Drying[8]	C. residue[9]	Total
		33	371	77	225	44	18	10	8	34	104	519.8[10]
		34	556	78	316	44	27	10	9	50	152	686.8
RMN	ID	43	378	70	162	-	19	6	1	34	106	397.1
RMS	CO	44	368	28	158	-	18	18	1	33	103	359.3
		45	450	60	192	-	22	15	1	41	124	456.6
NP	NE	50	222	49	125	-	11	8	1	20	65	278.4
		51	469	156	203	-	23	12	1	42	130	567.0
		52	618	186	280	-	30	11	2	56	168	734.2

Table E-3. Carbon equivalent emissions for soybean systems in the United States.

Region	State	Id[1]	Bu[2]	Carbon equivalent emissions (kg CE ha^{-1} yr^{-1})								
				Fuel [3]	Fertilizers[4]	Lime	Seed[5]	Pesticides[6]	T. inputs[7]	Drying[8]	C. residue[9]	Total
NLS	WI	3	136	60.9	29.7	-	34.0	17.9	1.8	-	64.7	209.0
CB	OH	8	91	27.5	8.6	24.0	22.8	22.5	5.1	-	58.2	168.7
		9	116	27.5	8.6	24.0	29.0	22.5	5.1	-	58.2	174.9
		10	138	27.5	10.3	24.0	34.6	22.5	5.2	-	65.5	189.6
	IA	17	111	86.5	8.6	-	27.8	23.0	1.7	-	56.5	204.1
		18	124	87.2	9.6	-	30.9	23.0	1.8	-	60.6	213.0
		19	136	88.2	10.5	-	34.0	23.1	1.8	-	64.7	222.2
SP	TX	22	148	178.5	5.1	-	37.1	21.1	1.3	-	68.7	311.7
		23	148	137.5	5.1	-	37.1	21.1	1.3	-	68.7	270.8
DS	AR	28	124	56.9	8.5	-	30.9	22.5	1.7	-	60.6	181.1
		29	124	58.5	8.5	-	30.9	22.5	1.7	-	60.6	182.6
		30	74	58.5	8.5	-	18.5	22.5	1.7	-	45.4	155.1
AP	TN	35	111	54.5	4.9	43.6	27.8	21.4	7.6	-	56.5	216.4
		36	148	54.5	4.9	43.6	37.1	21.4	7.6	-	68.7	237.8
NP	NE	56	153	196.3	-	-	38.3	21.4	1.0	-	70.4	327.4
		57	96	68.2	-	-	24.1	21.4	1.0	-	70.4	185.0
		58	146	187.5	-	-	36.4	21.4	1.0	-	70.4	316.7

[1]Crop system identifier for more information the reader is refers to Table E-1.

[2]Crop yields from crop budgets (2014), these budgets were transformed to bushels ha (1 ha = 2.47 acres)

[3]Calculated based on diesel fuel. This fuel has an emission factor of 10,180 g CO_2 per gallon and 2.77 kg C gal^{-1} (Federal Register 2010).

[4]Encompass carbon emissions from production, transportation, storage and distribution of agricultural chemicals: nitrogen (urea), triple super phosphate (P_2O_5) and potassium sulphate (K_2O). Likewise, N_2O transfer from synthetic fertilizer (IPCC 2013).

[5] Carbon emissions calculated based on the kg per ha with a moisture less than 12% for corn, soybean and winter wheat and 90% for potatoes.

[6] Calculations were based on active ingredients of the herbicides, insecticides and fungicides.

[7] Transport of all inputs from distribution centers and trucking based on 900 bushels loads, 6 mpg, oil and lube 10% of the fuel cost.

[8] Drying cost based on 2.5% of the moisture removed (0.02 gal of LP per percent of point of moisture removed) (Ohio State 2014), Crop moisture at harvest (20%) and crop moisture at storage (15%) (Beuerlein 2008).

[9] Crop residue based on the amount of carbon released by the plant material remaining after harvesting, including leaves, stalks, and roots.

Table E-4. Carbon equivalent emissions for wheat systems in the United States.

Region	State	Id	Bu	Carbon equivalent emissions (kg CE ha^{-1} yr^{-1})								
				Fuel	Fertilizers	Lime	Seed	Pesticides	T. inputs	Drying	C. residue	Total
NLS	WI	4	197.6	67.1	99.3	-	28.2	7.7	3.1	27.7	96.3	329.4
CB	OH	11	143.3	38.5	74.4	24.0	20.5	7.7	6.1	20.1	71.7	262.9
		12	177.8	38.5	54.4	24.0	25.4	7.7	6.1	24.9	87.3	268.3
		13	212.4	37.9	59.0	24.0	30.3	7.7	6.1	29.7	103.0	297.8
sp	TX	24	148.2	41.3	81.4	-	21.2	7.7	2.6	20.7	73.8	248.8
		25	160.6	54.4	81.4	-	22.9	7.7	2.6	22.5	79.5	271.1
DS	AR	31	148.2	53.9	155.0	-	21.2	7.7	3.3	20.7	73.8	335.5
AP	TN	37	148.2	73.7	106.0	43.6	21.2	7.7	8.9	20.7	73.8	355.6
RMN	ID	38	88.9	48.1	64.9	-	12.7	7.7	2.3	12.4	47.0	195.1
		39	123.5	43.4	115.8	-	17.6	7.7	2.6	17.3	62.7	267.0
		40	308.8	62.8	194.0	-	44.1	7.7	3.1	43.2	146.7	501.6
RMS	CO	46	86.5	34.9	54.1	-	12.4	7.7	2.2	12.9	48.3	172.4
		47	71.6	45.1	42.6	-	10.2	7.7	2.1	9.8	38.3	155.8
NP	NE	53	247.0	165.0	165.3	-	35.3	7.7	2.8	34.6	118.7	529.4
		54	123.5	52.9	78.0	-	17.6	7.7	2.4	17.3	62.7	238.6
		55	148.2	43.5	115.4	-	21.2	7.7	2.6	20.7	73.8	285.0

Table E-5. Carbon equivalent emissions for potato systems in the United States.

Region	State	Id	Carbon equivalent emissions (kg CE ha^{-1} yr^{-1})									
			Bu	Fuel	Fertilizers	Lime	Seed	Pesticides	T. inputs	Drying	C. residue	Total
RMN	ID	41	1,025.1	227.5	359.0	-	179.8	11.4	4.6	-	484.7	1,267.0
		42	864.5	233.4	328.9	-	151.7	7.7	4.1	-	409.9	1,135.8
RMS	CO	48	1,358.5	142.3	471.6	-	238.3	11.1	5.8	-	640.0	1,509.2
	MS	49	741.0	225.3	281.6	-	130.0	13.0	9.8	-	352.4	1,012.1

Table E-6. Mean size of rural houses built before and after 2000 in different regions of the United States.

Year built	Rural houses size (m^2) for Climatic Zone and Insulation Type[1]														
	1.W	1.A	1.P	2.W	2.A	2.P	3.W	3.A	3.P	4.W	4.A	4.P	5.W	5.A	5.P
<2000	295.9	274.5	195.8	316.8	271.3	251.6	266.0	238.3	246.5	227.4	201.3	174.7	219.1	158.0	142.5
>2000	292.7	316.2	226.0	386.0	315.5	176.3	330.9	284.7	233.4	270.6	265.5	255.6	284.8	253.6	211.9

[1]American Institute of Architecture: climate zone (1 to 5), W= well insulated, A= adequately insulated, P=poorly insulated.

Table E-7. Carbon equivalent (CE) emissions for rural houses built before and after 2000 using different energy sources and insulation types in different climatic zones.

Year built	Energy source	Rural houses emissions (Mg CE) for Climatic Zone and Insulation Type[1]														
		1.W	1.A	1.P	2.W	2.A	2.P	3.W	3.A	3.P	4.W	4.A	4.P	5.W	5.A	5.P
<2000	Electricity	1.5	1.9	2.1	1.5	1.7	1.8	2.4	2.6	2.5	2.7	2.9	3.1	3.0	4.1	4.0
	Natural gas	1.4	1.3	2.3	1.0	1.5	1.7	1.6	1.6	1.7	1.0	1.4	1.5	0.7	1.0	1.4
	Propane	0.9	1.2	1.9	1.3	1.5	2.2	0.9	0.8	0.9	0.8	0.7	1.1	0.8	0.4	1.1
	Fuel oil	1.2	1.3	1.8	1.4	1.7	1.6	1.3	1.4	1.4	0.8	0.0	0.0	0.0	0.0	0.0
>2000	Electricity	1.8	1.6	1.9	1.4	1.4	2.1	2.2	2.7	3.4	2.6	2.7	2.8	2.9	2.9	3.9
	Natural gas	2.0	1.2	1.3	1.3	1.5	1.2	1.0	1.6	2.0	1.3	1.4	1.7	1.0	0.9	0.7
	Propane	1.1	1.3	2.0	1.3	1.5	3.7	0.9	0.8	1.1	0.8	0.7	0.9	0.7	0.3	0.9
	Fuel oil	2.0	1.7	2.2	1.6	2.5	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0

[1]American Institute of Architecture: Climate Zone (1 to 5), Insulation type: W= well insulated, A= adequate insulated, P=poor insulated.

Table E-8. Carbon equivalent emissions for heating and cooling rural houses built before and after 2000 using different energy sources and insulation types in different climatic zones.

		Total energy usage for heating and cooling CE Mg														
Year built	Energy Source	1.W[1]	1.A	1.P	2.W	2.A	2.P	3.W	3.A	3.P	4.W	4.A	4.P	5.W	5.A	5.P
<2000	Electricity heating	0.4	0.4	0.4	0.3	0.3	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.3	0.5	0.5
	Electricity cooling	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.2	0.4	0.5	0.5	0.8	1.0	1.1
	Propane	1.1	1.3	1.7	1.1	1.1	1.1	0.7	0.8	0.9	0.8	0.8	1.0	0.3	0.6	0.9
	Total	**1.6**	**1.8**	**2.2**	**1.5**	**1.5**	**1.6**	**1.5**	**1.6**	**1.6**	**1.6**	**1.7**	**2.0**	**1.4**	**2.1**	**2.5**
>2000	Electricity heating	0.5	0.4	0.2	0.2	0.1	0.1	0.4	0.5	0.6	0.4	0.4	0.3	0.3	0.3	0.3
	Electricity cooling	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.4	0.2	0.5	0.6	0.7	1.0	1.0	1.2
	Propane	0.9	1.2	1.7	1.0	1.3	1.9	0.7	0.6	0.8	0.7	0.8	0.9	0.4	0.5	0.6
	Total	**1.5**	**1.7**	**2.0**	**1.4**	**1.5**	**2.2**	**1.4**	**1.5**	**1.6**	**1.6**	**1.8**	**1.9**	**1.7**	**1.8**	**2.1**

[1]American Institute of Architecture: Climate Zone (1 to 5), Insulation type: W= well insulated, A= adequate insulated, P=poor insulated.

Table E-9. Potential of windbreaks on different faming scenarios for avoiding carbon emissions.

Region	State	Crop system	System Code	Climatic zone	Scenarios for avoided emissions ($Mg\ CE\ yr^{-1}$)[1]					
					House built before 2000			House built after 2000		
					Farm size (ha)[2]			Farm size (ha)		
					Small (60)	Medium (300)	Large (600)	Small (60)	Medium (300)	Large (600)
NLS	WI	Corn	1	1	1.9[3]	7.4	14.3	1.7	7.3	14.2
		Corn	2	1	1.7	6.8	13.2	1.6	6.7	13.0
		Soybean	3	1	1.1	3.4	6.3	1.0	3.3	6.1
		wheat	4	1	1.4	5.2	9.9	1.3	5.2	9.8
CB	OH	Corn	5	2	1.6	6.4	12.4	1.5	6.4	12.4
		Corn	6	2	1.8	7.4	14.4	1.7	7.4	14.4
		Corn	7	2	2.0	8.4	16.4	1.9	8.4	16.4
		Soybean	8	2	0.9	2.8	5.3	0.8	2.8	5.2
		Soybean	9	2	0.9	2.8	5.3	0.8	2.8	5.2
		Soybean	10	2	0.9	3.0	5.6	0.9	2.9	5.5
		Wheat	11	2	1.1	4.2	8.1	1.1	4.2	8.0
		Wheat	12	2	1.1	4.2	8.1	1.1	4.2	8.0
		Wheat	13	2	1.2	4.6	8.8	1.2	4.6	8.8
	IA	Corn	14	2	1.7	7.1	13.9	1.7	7.1	13.9
		Corn	15	2	1.9	7.9	15.4	1.8	7.8	15.3
		Corn	16	2	1.9	8.1	15.9	1.9	8.1	15.9

[1] Values from CE emissions for different cropping systems and energy used for heating and cooling of adequately insulated farmstead houses. Reduced CE emissions for crop system were calculated in the 5% of the agricultural land take out from crop by field windbreaks while in farmstead, the effect of windbreaks in reduction of CE emissions for space heating was 25% and for air conditioning 10%.

[2] The calculations for farm size were 58, 178 and 597 ha for small, medium and large farm, respectively. To obtain the value for ha basis divide for these

[3] The value come from 5% of the corn emissions (Appendix Table E-2,id. 1) of a small farm located in climate zone 1, emitting 26.85 Mg CE (0.463*58), 25% and 10% of the reduced emissions for space heating and cooling respectively in a adequately insulated farmstead built before 2000 (Appendix Table E-5).

Table E-9. (con't)

Region	State	Crop system	System Code	Climatic zone	Scenarios for avoiding emissions (Mg CE yr^{-1})[1]					
					House built before 2000			House built after 2000		
					Farm size (ha)			Farm size (ha)		
					Small (60)	Medium (300)	Large (600)	Small (60)	Medium (300)	Large (600)
		Soybean	17	2	1.0	3.3	6.2	0.9	3.3	6.2
		Soybean	18	2	1.0	3.4	6.4	0.9	3.3	6.3
		Soybean	19	2	1.0	3.5	6.6	1.0	3.4	6.5
SP	TX	Corn	20	5	1.2	4.3	8.1	1.0	4.1	7.9
		Corn	21	5	2.8	12.5	24.7	2.6	12.3	24.5
		Soybean	22	5	1.3	4.8	9.1	1.1	4.6	9.0
		Soybean	19	2	1.1	4.2	7.9	1.0	4.0	7.7
		Soybean	23	5	1.1	4.0	7.6	0.9	3.8	7.5
		Wheat	24	5	1.2	4.3	8.3	1.0	4.1	8.1
		Wheat	25	5	1.2	4.3	8.1	1.0	4.1	7.9
DS	AR	Corn	26	4	1.9	8.6	17.0	2.0	8.7	17.0
		Corn	27	4	1.5	6.7	13.0	1.6	6.7	13.1
		Soybean	28	4	0.8	2.8	5.3	0.8	2.9	5.4
		Soybean	29	4	0.8	2.8	5.4	0.8	2.9	5.4
		Soybean	30	4	0.8	2.6	4.9	0.8	2.7	5.0
		Wheat	31	4	1.3	5.2	10.1	1.3	5.3	10.2
AP	TN	Corn	32	4	1.8	7.9	15.5	1.8	7.9	15.5
		Corn	33	4	1.8	8.1	15.9	1.9	8.2	16.0
		Corn	34	4	2.3	10.5	20.6	2.3	10.5	20.7

Table E-9. (con't)

Region	State	Crop system	System Code	Climatic zone	Scenarios for avoiding emissions (Mg CE yr^{-1})[1] House built before 2000, Farm size (ha): Small (60)	Medium (300)	Large (600)	House built after 2000, Farm size (ha): Small (60)	Medium (300)	Large (600)
		Soybean	35	4	0.9	3.4	6.5	1.0	3.4	6.5
		Soybean	36	4	0.9	3.6	6.8	1.0	3.6	6.9
		Wheat	37	4	1.3	5.5	10.7	1.4	5.6	10.8
RMN	ID	Wheat	38	1	1.1	3.5	6.4	1.0	3.3	6.3
		Wheat	39	1	1.3	4.5	8.4	1.2	4.3	8.3
		Wheat	40	1	1.9	7.6	14.6	1.8	7.4	14.5
		Potato	41	1	3.7	17.0	33.6	3.6	16.9	33.5
		Potato	42	1	3.4	15.5	30.5	3.3	15.4	30.4
		Corn	43	1	1.7	6.5	12.5	1.6	6.4	12.3
RMS	CO	Corn	44	1	1.6	5.9	11.4	1.4	5.8	11.2
		Corn	45	1	1.8	7.3	14.1	1.7	7.2	14.0
		wheat	46	1	1.0	3.1	5.7	0.9	3.0	5.6
		wheat	47	1	1.0	2.9	5.3	0.9	2.8	5.2
		Potato	48	1	4.3	19.8	39.1	4.1	19.7	39.0
NE	MA	Potato	49	1	3.3	14.6	28.8	3.1	14.5	28.7
NP	NE	Corn	50	2	1.2	4.7	9.0	1.2	4.7	9.0
		Corn	51	2	2.0	8.8	17.3	2.0	8.8	17.2
		Corn	52	2	2.5	11.2	22.1	2.5	11.2	22.0
		Wheat	53	2	1.9	8.0	15.6	1.8	7.9	15.5
		Wheat	54	2	1.1	3.9	7.4	1.0	3.9	7.4
		Wheat	55	2	1.2	4.5	8.7	1.2	4.5	8.7

Table E-9. (con't)

Region	State	Crop system	System Code	Climatic zone	Scenarios for avoiding emissions (Mg CE yr^{-1})[1]					
					House built before 2000			House built after 2000		
					Farm size (ha)			Farm size (ha)		
					Small (60)	Medium (300)	Large (600)	Small (60)	Medium (300)	Large (600)
		Soybean	56	2	1.3	5.0	9.6	1.2	4.9	9.5
		Soybean	57	2	0.9	3.1	5.7	0.9	3.0	5.7
		Soybean	58	2	1.3	4.8	9.3	1.2	4.8	9.3

APPENDIX F. IMPACT OF WINDBREAKS ON THE C BALANCE FOR DIFFERENT FARMING SCENARIOS.

Table F-1. Performance of different windbreak designs to store carbon and reduce emissions on large farms with different cropping systems in the Northern Plains region (Nebraska).

Field Windbreak Design	Storage ($Mg\ C\ yr^{-1}$)[1] Windbreaks: Field	Storage ($Mg\ C\ yr^{-1}$)[1] Windbreaks: Farmstead[4]	Avoided emissions[2] ($Mg\ C\ yr^{-1}$)	Total[3] ($Mg\ C\ yr^{-1}$)
One row small coniferous	83.6	7.4	4.2	95.1
One row tall deciduous	35.7	7.4	5.4	48.5
One row tall coniferous	44.9	7.4	3.7	56.0
Two rows tall deciduous	43.7	7.4	11.1	62.1
Two rows tall coniferous	66.2	7.4	10.5	84.1
One row tall coniferous and one row tall deciduous	55.7	7.4	10.9	73.9
One row tall coniferous and one row small conifer	100.9	7.4	10.0	118.3
One row tall deciduous and one row small conifer	91.6	7.4	10.3	109.3
Three rows tall coniferous	111.4	7.4	17.5	136.3
Three row tall deciduous	71.8	7.4	17.9	97.1
Two rows tall deciduous and one row tall coniferous	84.8	7.4	17.7	109.9
One row tall deciduous, one row tall coniferous and one row small coniferous	99.3	7.4	17.1	123.8

[1] Calculations for a 600 ha farm growing corn (52), soybean (54) and winter wheat (56) systems, each on 1/3 of the cropland area, with a farmstead of 3 ha containing a house of 250 m^2 protected by a 300 m long 8-row windbreak.

[2] The total emissions in the cropping area were estimated at 260.6 $Mg\ CE\ yr^{-1}$ and the reduced emissions were calculated in the area occupied by field and farmstead windbreaks.

[3] [3] Impact of the windbreaks on the carbon budget of different farming scenarios.

[4] farmstead CE emissions were fixed for all farming scenarios.

Table F-2. Performance of different windbreak designs to store carbon and reduce emissions on large farms with different cropping systems in the Southern Plains region (Texas).

Field Windbreak Design	Storage (Mg C yr^{-1})[1] Windbreaks Field	Storage (Mg C yr^{-1})[1] Windbreaks Farmstead	Avoided emissions[2] (Mg C yr^{-1})	Total[3] (Mg C yr^{-1})
One row small coniferous	101.6	3.3	4.0	108.9
One row tall deciduous	53.6	3.3	5.1	62.0
One row tall coniferous	45.9	3.3	3.5	52.7
Two rows tall deciduous	65.6	3.3	10.6	79.5
Two rows tall coniferous	67.6	3.3	10.1	81.0
One row tall coniferous and one row tall deciduous	67.2	3.3	10.4	80.9
One row tall coniferous and one row small conifer	116.6	3.3	9.6	129.5
One row tall deciduous and one row small conifer	117.2	3.3	9.9	130.4
Three rows tall coniferous	113.8	3.3	16.8	133.9
Three row tall deciduous	107.8	3.3	17.3	128.4
Two rows tall deciduous and one row tall coniferous	109.2	3.3	17.0	129.5
One row tall deciduous, one row tall coniferous and one row small coniferous	120.2	3.3	16.5	139.9

[1] Calculations for a 600 ha farm growing corn (20), soybean (22) and winter wheat (25) systems, each on 1/3 of the cropland area, with a farmstead of 3 ha containing a house of 250 m^2 protected by 300 m long 3 rows windbreak.
[2] The total emissions in the cropping area were estimated at 166.6 Mg CE yr^{-1} and the reduced emissions were calculated in the area occupied by field and farmstead windbreaks.
[3] [3] Impact of the windbreaks on the carbon budget of different farming scenarios.
[4] farmstead CE emissions were fixed for all farming scenarios.

Table F-3. Performance of different windbreak designs to store carbon and reduce emissions on large farms with different cropping systems in the Rocky Mountains North region (Idaho).

Field Windbreak Design	Storage (Mg C yr^{-1})[1] Windbreaks Field	Storage (Mg C yr^{-1})[1] Windbreaks Farmstead	Avoided emissions[2] (Mg C yr^{-1})	Total[3] (Mg C yr^{-1})
One row small coniferous	57.5	6.6	8.3	72.4
One row tall deciduous	64.3	6.6	10.7	81.6
One row tall coniferous	38.2	6.6	7.3	52.1
Two rows tall deciduous	78.7	6.6	22.4	147.7
Two rows tall coniferous	56.4	6.6	21.4	84.4
One row tall coniferous and one row tall deciduous	67.8	6.6	22.1	96.5
One row tall coniferous and one row small conifer	74.6	6.6	20.3	101.5
One row tall deciduous and one row small conifer	85.6	6.6	20.8	113.0
Three rows tall coniferous	94.9	6.6	35.7	137.2
Three row tall deciduous	129.4	6.6	36.6	172.6
Two rows tall deciduous and one row tall coniferous	117.0	6.6	36.1	159.2
One row tall deciduous, one row tall coniferous and one row small coniferous	99.6	6.6	34.9	141.1

[1] Calculations for a 600 ha farm growing potato (42), corn (43) and winter wheat (39) systems, each in 1/3 of the cropland area, with a farmstead of 3 ha containing a house of 250 m^2 protected by 300 m long 10 rows windbreak.

[2] The total emissions in the cropping area were estimated at 350.0 Mg CE yr^{-1} and the reduced emissions were calculated in the area occupied by field and farmstead windbreaks.

[3] [3] Impact of the windbreaks on the carbon budget of different farming scenarios

[4] farmstead CE emissions were fixed for all farming scenarios.

Table F-4. Performance of different windbreak designs to store carbon and reduce emissions on large farms with different cropping systems in the Corn Belt region (Iowa).

Field Windbreak Design	Storage (Mg C yr^{-1})[1] Windbreaks		Avoided emissions[2] (Mg C yr^{-1})	Total[3] (Mg C yr^{-1})
	Field	Farmstead		
One row small coniferous	105.7	6.6	5.1	117.5
One row tall deciduous	33.2	6.6	6.6	46.4
One row tall coniferous	35.1	6.6	4.5	46.2
Two rows tall deciduous	40.6	6.6	13.6	60.9
Two rows tall coniferous	51.7	6.6	13.0	71.4
One row tall coniferous and one row tall deciduous	46.7	6.6	13.4	66.7
One row tall coniferous and one row small conifer	112.5	6.6	12.4	131.5
One row tall deciduous and one row small conifer	109.1	6.6	12.7	128.4
Three rows tall coniferous	87.1	6.6	21.6	115.3
Three row tall deciduous	66.7	6.6	22.2	95.5
Two rows tall deciduous and one row tall coniferous	73.2	6.6	21.9	101.7
One row tall deciduous, one row tall coniferous and one row small coniferous	100.4	6.6	21.2	128.2

[1] Calculations for a 600 ha farm growing corn (15) and soybean (17) systems, each in 1/2 of the cropland area, with a farmstead of 3 ha containing a house of 250 m^2 protected by 300 m long 8 rows windbreak.
[2] The total emissions in the cropping area were estimated at 214.4 Mg CE yr^{-1} and the reduced emissions were calculated in the area occupied by field and farmstead windbreaks.
[3] Impact of the windbreaks on the carbon budget of different farming scenarios.
[4] farmstead CE emissions were fixed for all farming scenarios.